E-Journal of Advanced Maintenance Vol. 11 No. 1 (2019) 46-64
Japan Society of Maintenology

X-band electron LINAC-based compact neutron source for nuclear debris on-site screening using short-distance neutron resonance transmission analysis

Yudhitya KUSUMAWATI[1,*], Issei OZAWA[1], Yuki MITSUYA[1], Tomooki SHIBA[2] and Mitsuru UESAKA[1]

[1] *Department of Nuclear Engineering and Management, School of Engineering, The University of Tokyo, Tokyo 113-8654, Japan*
[2] *Integrated Support Center for Nuclear Nonproliferation and Nuclear Security (ISCN) and Collaborative Laboratories for Advanced Decommissioning Science (CLADS), Japan Atomic Energy Agency, Ibaraki 319-1184, Japan*

ABSTRACT

Unaccountable nuclear fuel debris is subject to nuclear safeguards and criticality safety, and their removal is one of the decommissioning activities of the TEPCO Fukushima Daiichi Nuclear Power Plant (The 1F). In order to significantly contribute to efficient debris retrieval, an on-site nuclear debris screening system consisted of non-destructive analysis using both X-ray and neutron source is being developed. By realizing a compact pulsed neutron source system from a 3.95 MeV X-band electron LINAC coupled with tungsten and beryllium as photon and neutron converters respectively, on-site short-distance neutron resonance transmission analysis (NRTA) can be performed to confirm the existence of U/Pu in a nuclear debris sample. Experiment result shows that neutron TOF energy spectrum up to 70 eV with 4% energy resolution can be measured within only 2.5 m of neutron flight path through a ^{3}He proportional counter. NRTA experiments using mixed model samples indicate that multiple resonance peaks in the neutron energy spectrum up to 20 eV, where resonance peaks of major U/Pu isotopes fall within this range, can be simultaneously observed. The proof-of-principle experiment was successfully performed. Short-distance NRTA would be an important complementary method for database calibration of polychromatic X-ray CT system of nuclear debris, which can provide estimation of U/Pu distribution data necessary for nuclear debris activity mapping of The 1F reactor core area.

KEYWORDS

isotope identification; neutron resonance; neutron source; on-site measurement; time of flight; transmission; X-band

ARTICLE INFORMATION

Article history:
Received 7 January 2019
Accepted 3 March 2019

1. Introduction

Nuclear fuel debris removal is one of the decommissioning activities of the TEPCO Fukushima Daiichi Nuclear Power Plant (The 1F), which is important for the purpose of nuclear safety and security, and contribution to local people's life and economic recovery. However, one of the main problems associated with this activity is the uncertainty of the radioactivity distribution in the target fuel debris. By analyzing the debris samples recovered from the reactor by a robot, a detailed mapping of the physical and chemical properties of the fuel debris lumps present in the reactor should be able to be obtained. If this can be realized, it would significantly contribute to efficient debris retrieval and the reduced exposure of workers to radiation. In particular, the necessary information for application to metrological control is the distribution of uranium and plutonium content in fuel debris lumps. Therefore, for this purpose, a method of analyzing the debris and determining its composition on-site is required. Some established methods on nuclear debris analysis like laser-induced breakdown spectroscopy (LIBS) which can be used on-site nuclear reactor core [1]. However, as the analyzed sample would be instantaneously evaporated to induce light-emitting plasma, it would be difficult to obtain the weight information of the debris as well. On the other hand, induction coupling plasma

*Corresponding author, E-mail: yudhitya.k@gmail.com

mass spectrometer (ICP-MS) method that has been established by IRID to analyze Fukushima Daiichi nuclear debris [2] has minimum destructive effect to the sample, but it is not available for on-site use.

Our research team's proposal is to realize an on-site non-destructive analysis method for nuclear debris at The 1F by making use of the mobile, compact-sized, high-frequency X-band electron LINAC to construct a LINAC-based X-ray and neutron source. The diagram in Fig. 1 shows the flow of on-site screening of nuclear debris activity by utilizing two kinds of measurement technologies through LINAC-based beam source of X-ray and neutron. Both methods are important and complement each other.

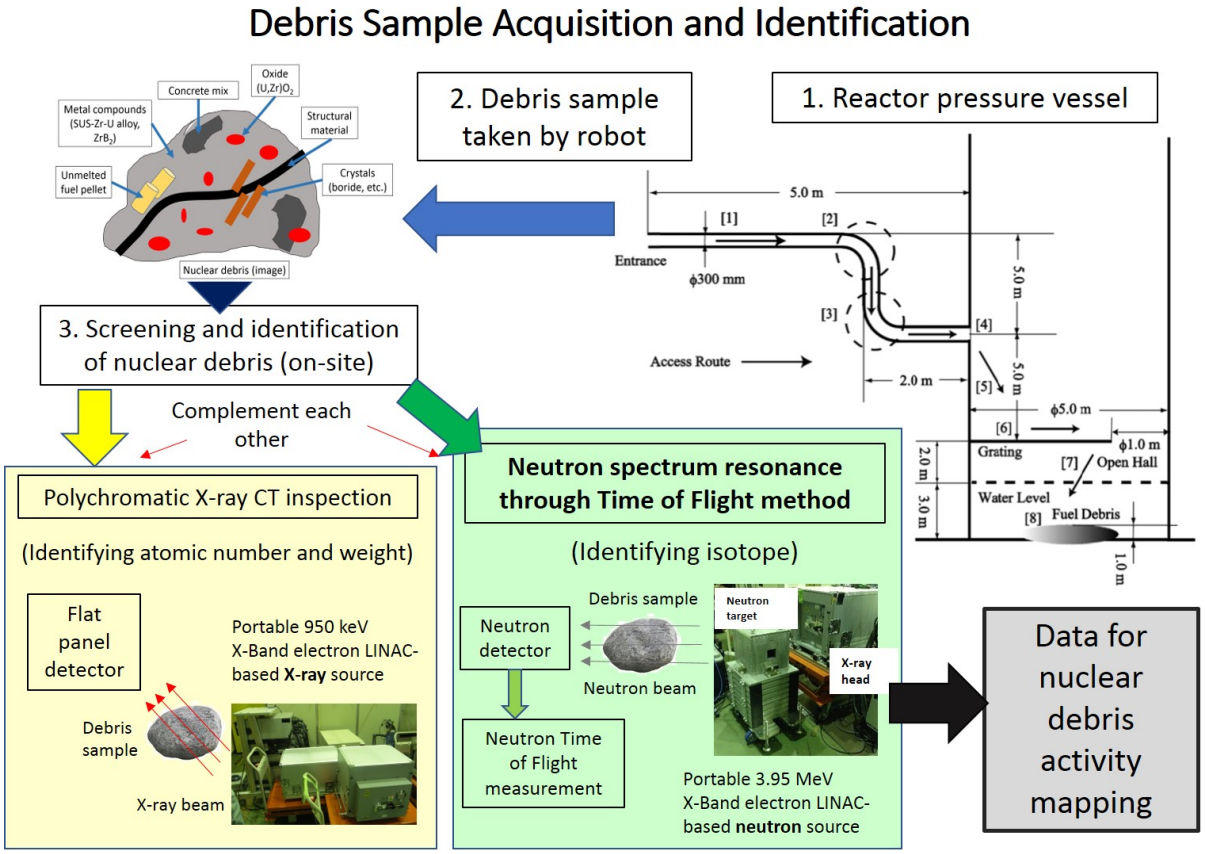


Fig. 1. Schematic of on-site nuclear debris screening activity to obtain the data for nuclear debris activity mapping (reactor pressure vessel map from [3]).

In regards to the inspection methods incorporated for on-site screening system, X-ray CT will be the one to provide quantitative data of nuclear debris size and imaging necessary for nuclear debris activity data. Polychromatic X-ray CT method was chosen as it has very good capability of identifying material with large gap on their atomic number (Z). It is suitable for detecting uranium and plutonium as both have the highest Z number among other materials contained in the nuclear debris (more explanations regarding this method and experiment result will be explained in later chapter). Even so, it is difficult to set a proper thresholding in order to get accurate identification of materials with close Z number [4], which would be the downside of this method in clear differentiation between uranium and plutonium. The two radioactive elements have very different microscopic cross-section value where plutonium microscopic cross-section is 200 times larger than uranium microscopic cross-section. This characteristic would make plutonium to be more reactive and prone to reach critical condition faster. Therefore, it is necessary to be able to distinguish between uranium and plutonium when handling the screening and analysis of nuclear debris' contents. For this purpose, another nuclear debris screening method which can determine the existence of uranium and plutonium with higher accuracy to complement the X-ray CT imaging result is needed.

Local nuclear waste facility Ningyo-Toge has established several techniques on uranium and

plutonium identification in spent nuclear fuel such as fast neutron direct interrogation and gamma-ray to determine enrichment [5]. But these methods are mainly applicated to uniform, large quantity nuclear waste drums, aside from the measurement equipment being heavy and stationary. Therefore, it would be unsuitable for the purpose of this research, as its approach is the on-site screening. Measurement targets are the smaller, mixed-elements nuclear debris just to provide a rough estimation of criticality before it is stored in the waste drums. According to the simulation of nuclear debris formation through slow and rapid cooling performed by Kazakhstan National Nuclear Center (NNC), the reactor core nuclear debris are expected to be rock-shaped and powder-shaped with average diameter of 5~10 mm [6].

One of other practical methods for identifying the mixed composition of a nuclear debris sample is via neutron resonance transmission analysis (NRTA). In NRTA, the neutron energy is measured via a neutron time-of-flight (TOF) method using a pulsed neutron source, which enables the specification of the neutron energy to be absorbed by the corresponding nuclide in the sample. As a reference regarding this method, a research on uranium and other minor actinides identification for Fukushima nuclear debris using NRTA has been conducted by the cooperation between Japan Atomic Energy Agency (JAEA) and Joint Research Center (JRC) [7]. Their main subject for identification is the rock-like and particle-like mixed-elements nuclear debris, which analysis is more complex and challenging due to their uncertainties in various aspects. They did an experiment using Geel Electron Linear Accelerator (GELINA) with 100 MeV energy and flight path of 10-12.5 meters. As the result, they have successfully identified each element contained in a mixed sample that represents nuclear debris.

It is proved that NRTA could be an effective way to analyze mixed-elements nuclear debris. However, many existing pulsed neutron sources are large in size and require a long flight path, and therefore, on-site use near the site of the nuclear reactor is impossible. On the other hand, transporting a sample to the large neutron TOF facility is not possible, since the transportation of fuel debris is strongly limited by the management in regards to nuclear security. In this case, there is a need for a compact and portable pulsed neutron source that can be used for on-site NRTA in the decommissioning operations, capable of short-distance TOF within a few meters. Through analytical calculations, it was determined that 2.5 m of TOF can only measure neutron energies up to 100 eV. Using this information as reference, we can determine the list of uranium and plutonium isotopes with neutron energy absorption values below 100 eV, where those isotopes will be the identification targets for this on-site NRTA system. Based on the Japanese Evaluated Nuclear Data Library (JENDL) reference of neutron reactions cross-section values for each isotope and considering their abundance, the isotopes subjected to identification would be ^{238}U, ^{235}U, ^{239}Pu, ^{240}Pu, and ^{242}Pu [8].

Figure 2 shows the result of an NRTA Monte Carlo simulation using PHITS with compact neutron source that produces a total of 10^8 neutron. The flight path length is set at 2.5 meters, based on estimation of the distance needed to obtain up to 100 eV neutron energy spectrum. Setting for the measurement sample is a plate of uranium and plutonium mix containing the aforementioned isotopes with size of 30×10 mm^2 and 0.5 mm thickness. The neutron detector is ^{3}He proportional counter with dimension of $30 \times 10 \times 30$ mm^3 and 2 atm pressure. This simulation result shows that the positions of the resonance peaks of plutonium and uranium isotopes occur in different neutron energy ranges and can be distinguished from each other. According to the plot, the resonance peaks for isotopes of plutonium are in the 0.1–5 eV range of the neutron energy spectrum, and 6–50 eV for isotopes of uranium.

Based on this information, our objective for this on-site screening system is to observe these selected resonance peaks to confirm the existence of uranium and plutonium in a nuclear debris sample, as pictured in Fig. 3. In this investigation, the demonstration of short-distance TOF measurement and NRTA using a compact and portable neutron source was conducted for analyzing nuclear fuel debris. This was realized by combining an X-ray source with photonuclear target. X-band electron LINAC with a maximum energy of 3.95 MeV was coupled with a tungsten target to produce X-rays. A beryllium block serves as the photonuclear target, and a ^{3}He proportional counter was used for neutron detector. For the TOF line at 2.5 m, the measurement of the resonance absorption of the neutrons in the region of 0.1–70 eV, which is the energy region usable for specifying ^{238}U, ^{235}U, ^{239}Pu, ^{240}Pu, and ^{242}Pu, was demonstrated.

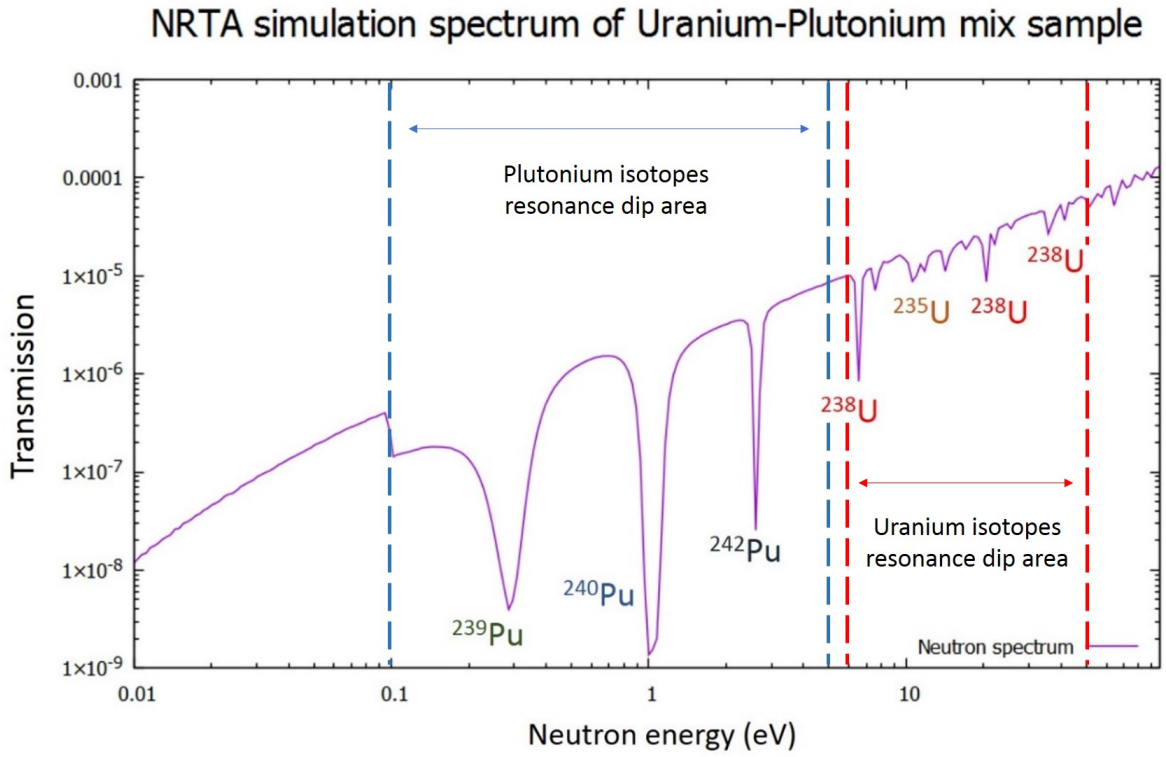


Fig. 2. Plot of an NRTA simulation result for a material with different contents. The resonance peaks represent the specific isotopes (only ^{238}U, ^{235}U, ^{239}Pu, ^{240}Pu, and ^{242}Pu were used in this simulation).

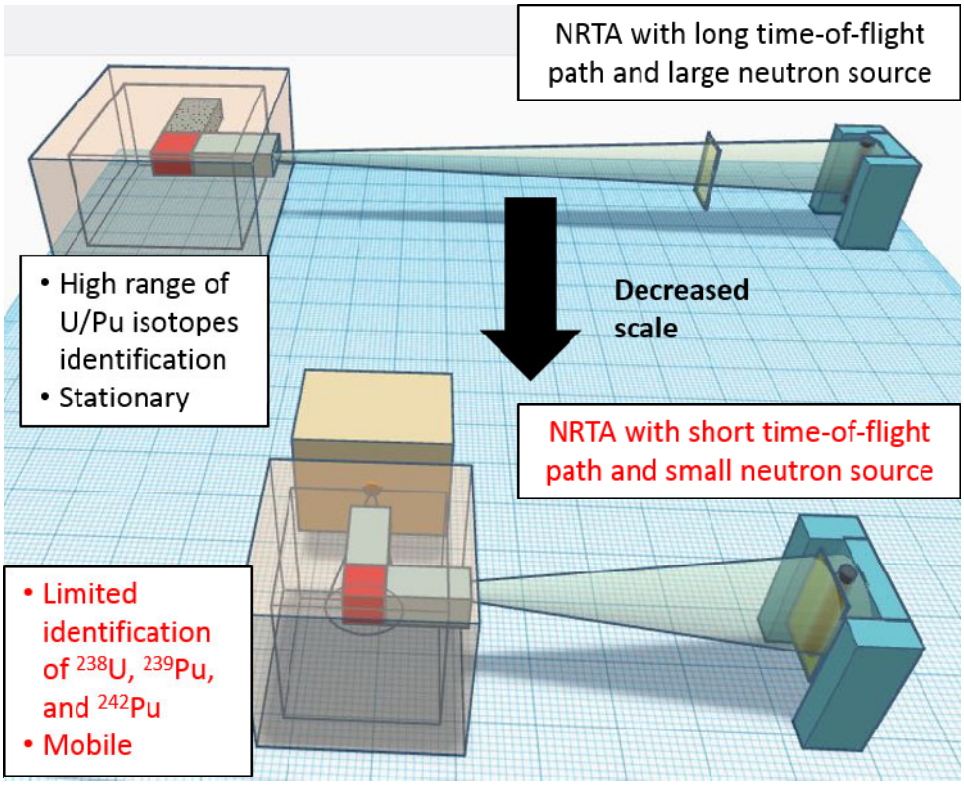


Fig. 3. Diagram of the short-distance time-of-flight concept for research objective.

2. Short-distance TOF system using X-band electron LINAC-based neutron source

A pulsed neutron source is needed to perform neutron TOF measurements. Usually, this kind of neutron source is produced by a large-sized, high-energy particle linear accelerator. However, by using the X-band type electron LINAC, which is characterized by a small size with a high frequency, the size of the neutron source can be greatly reduced, and there is even the potential for mobile use. Unlike neutron sources based on $^{2}H(d,n)^{3}He$ (D-D) or $^{3}H(d,n)^{4}He$ (D-T) fusion reactions, which target materials are radioactive substances requiring special control, a pulsed neutron source with high mobility can be realized by using beryllium target. A previous study on the utilization of compact 5 MeV electron LINAC to produce pulsed neutron using beryllium has been successfully proven [9], and becomes the reference of the current neutron target. In other related research, 3.95 MeV X-band electron LINAC has been successfully utilized for on-site non-destructive infrastructure inspection [10]. The neutron source version with additional neutron target has also been developed for moisture detection in bridge structure [11].

By combining 3.95 MeV X-band LINAC-based X-ray source system with a beryllium target, a compact and portable pulsed neutron source can be assembled. The 3.95 MeV compact neutron source has a relatively short pulse width of 1–4 μs, which enables TOF measurements at a short distance of approximately several meters. Figures 4, 5 and 6 show the schematic of the X-band electron LINAC-based neutron source, and Table 1 lists its parameters. With an approximate total size of 1 m^2 (not including the neutron flight path), it is a very compact pulsed neutron source system with high mobility.

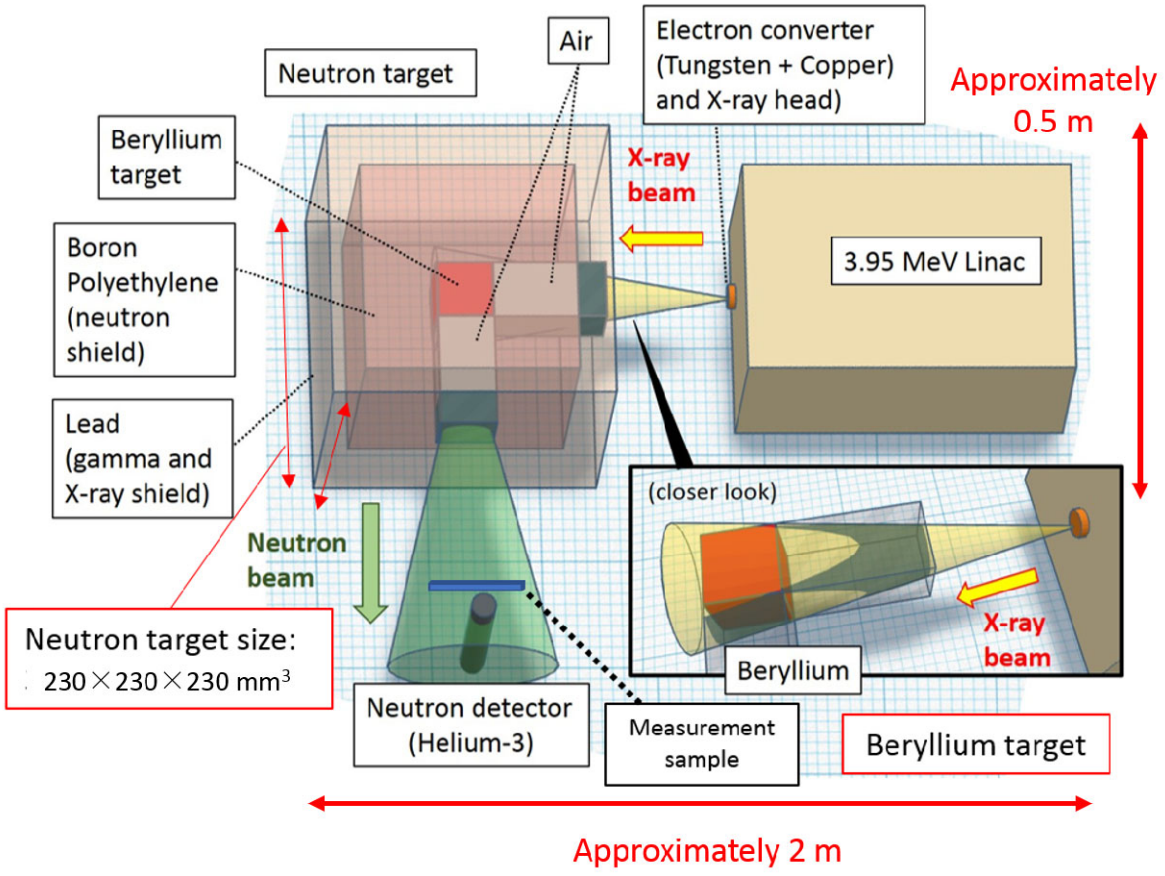
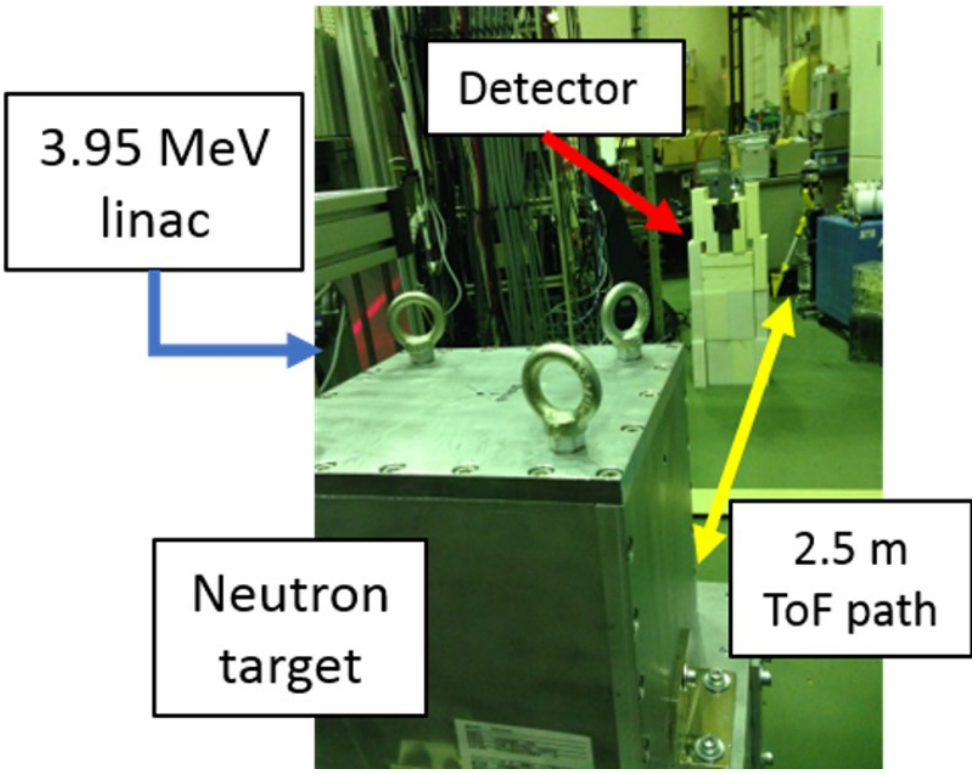
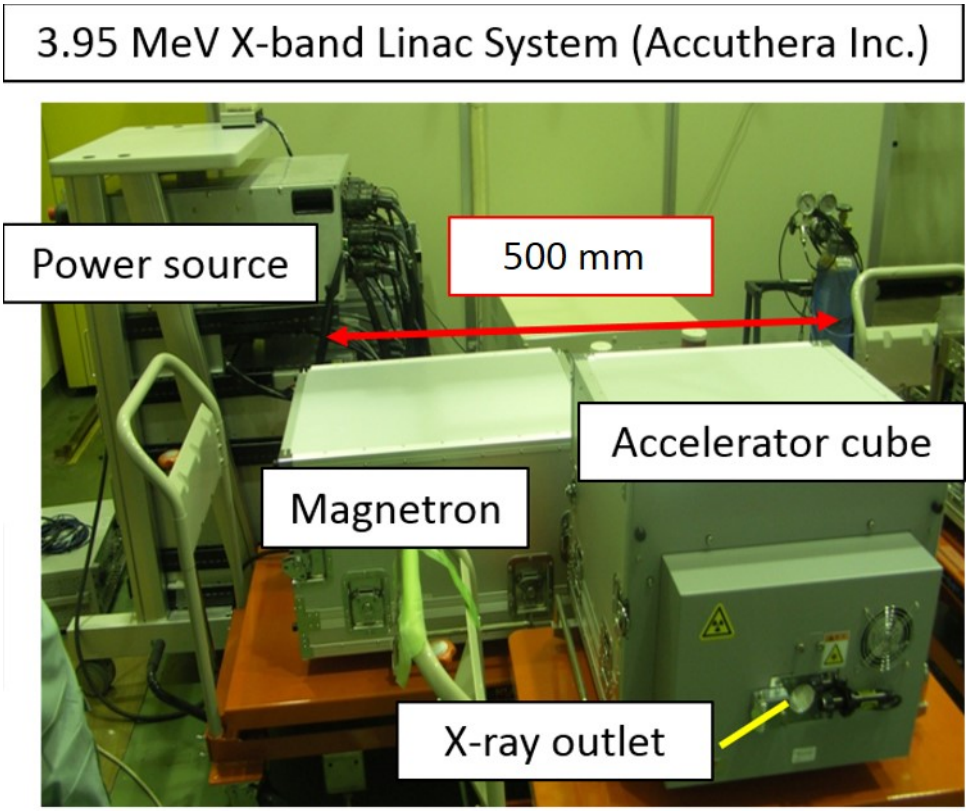


Fig. 4. Schematic of the compact X-band electron LINAC-based neutron source.



(a) Neutron TOF measurement setup



(b) 3.95 MeV electron LINAC

Fig. 5. Images of the short-distance TOF experiment setup. (a) neutron TOF measurement setup and (b) 3.95 MeV electron LINAC.

Fig. 6. Image of the 3.95 MeV electron LINAC with neutron target.

Table 1. Parameters of the 3.95 MeV X-band electron LINAC-based neutron source [12].

	3.95 MeV
Operating frequency	9.3 GHz
RF source	Magnetron
Input RF power	930 kW
Length of acceleration tube	500 mm
Form of acceleration tube	Side coupled structure
Accelerating cell	Half 1 + full 20
Number Cells coupling	3%
Filling time	0.23 μs
Shunt impedance	110-130 MΩ/m (Regular part)
Focusing fashion	RF focusing
Voltage of electron gun	20 KV
Electron gun type	Triode
Electron beam size	5 mm
Beam energy	3.95 MeV
Beam current	80 μA
Pulse width	2.5 μs
Pulse frequency	220 pulses/s
Tungsten target size (ø×thickness)	5×0.5 mm
Neutron intensity (calculation)	3.86×10^{7} n/ s

The 100-kilograms photo-neutron target was composed of 230×230×230 mm^3 cube of lead which mainly serves as gamma ray shielding, filled with boric acid resin layer for neutron shielding

and lead beam collimator. An L-shaped empty space is available inside to put in beryllium, as well as collimator for X-ray and neutron beam. By using Monte-Carlo code and PHITS, the simulation of this pulsed neutron source shows that the neutron yield is 7.13×10^6 n/s at the surface of the beryllium. Figure 7 shows the schematic of the neutron target used in this compact neutron source system [11]. In order to be able to get resonance neutron within the energy of 100 eV, a polyethylene neutron moderator with 20 mm thickness was put in front of the beryllium inside the lead beam collimator.

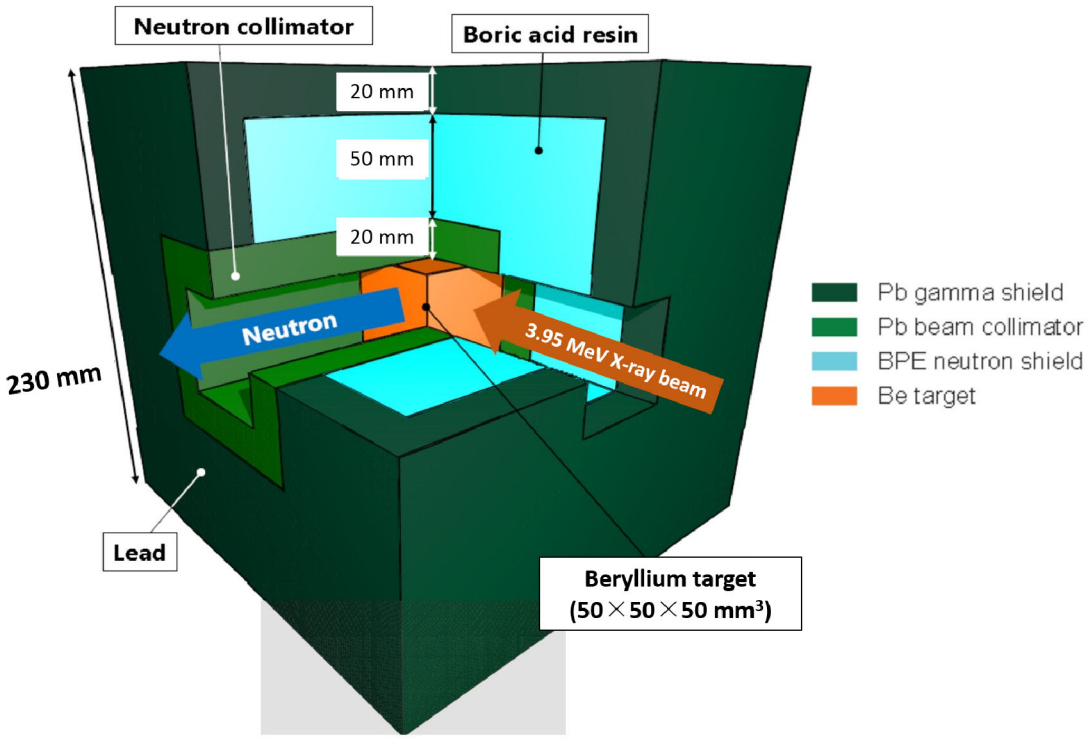


Fig. 7. Schematic of the neutron target in compact neutron source.

3. Experiment on neutron TOF measurement

Experiments on neutron TOF measurements using a compact neutron source system have been performed and Fig. 8 shows the experimental setup used. The setup is divided into three main components: neutron source component, signal amplifier component, and digital signal processing component. The realized configuration of the neutron detector in the neutron source part is shown in Fig. 9.

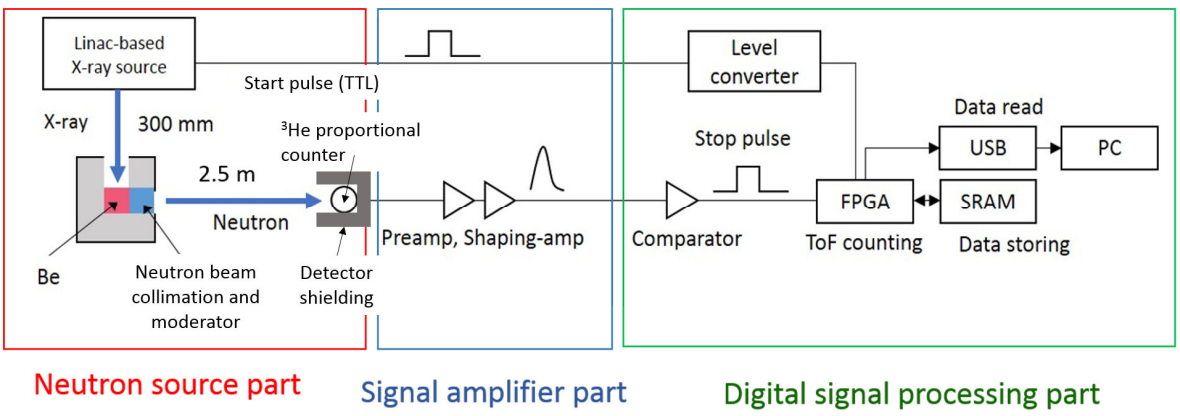


Fig. 8. Experimental setup to measure neutron TOF.

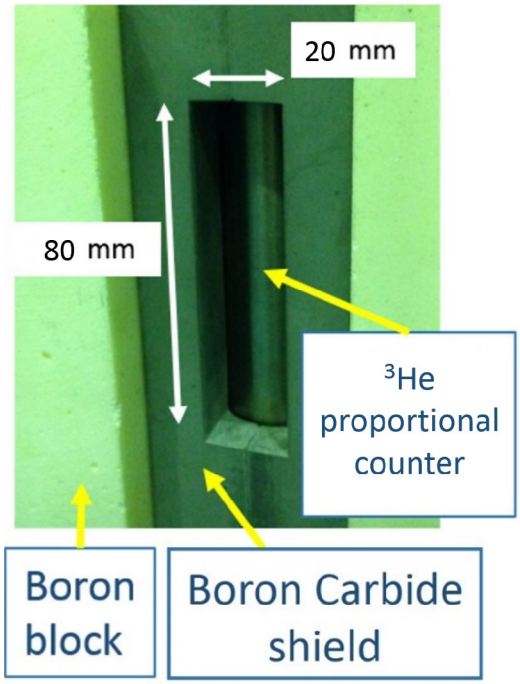


Fig. 9. Neutron detector window setup. Boron Carbide was used as housing for ^{3}He proportional counter, with additional boron block for shielding.

In the neutron source component, the X-band electron-LINAC based neutron source produced pulsed neutrons, which were detected by the ^{3}He proportional counter. Then in the digital signal processing component, neutron TOF is acquired using a field-programmable gate array (FPGA). The recorded data is later manually converted to an energy axis and plotted into a neutron energy spectrum graph. An example of an acquired neutron spectrum for 1-hour measurement is shown in Fig. 10.

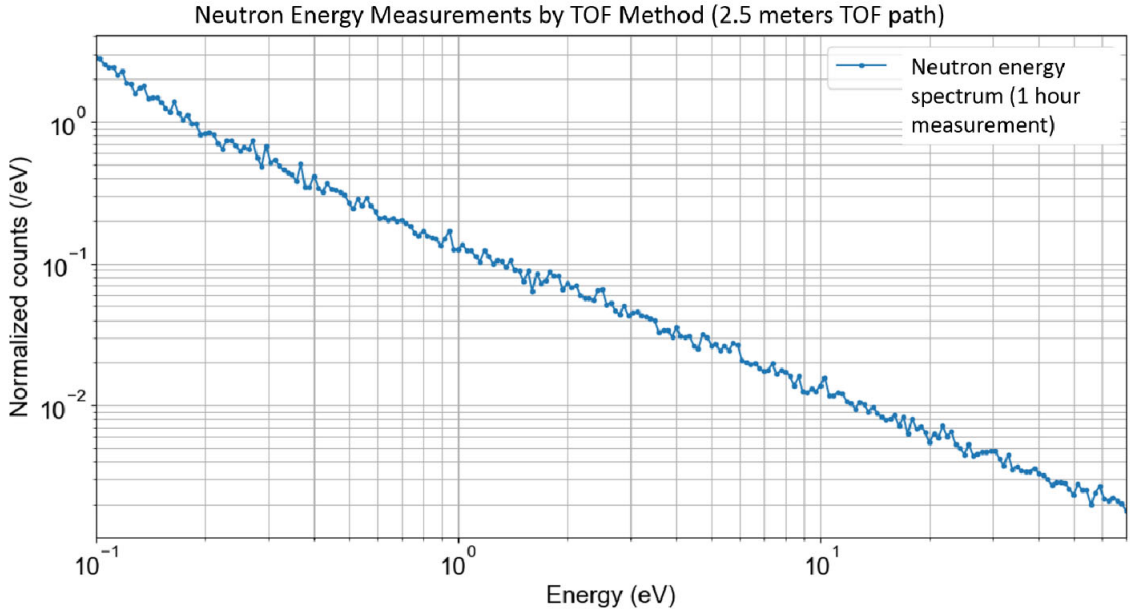


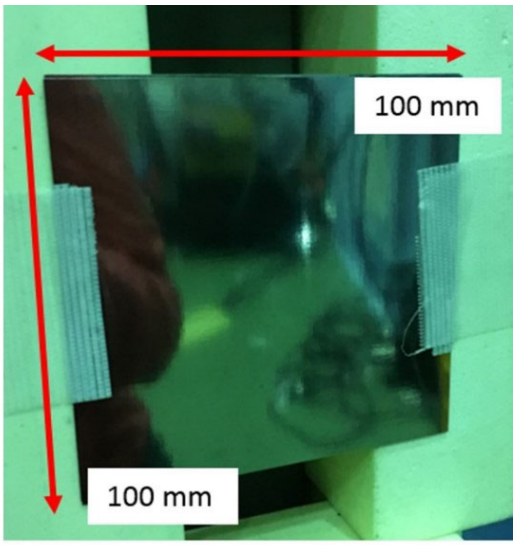
Fig. 10. Neutron energy spectrum obtained from 3.95 MeV X-band electron LINAC-based neutron source.

From the result, the observable pulsed neutron spectrum energy range is up to 70 eV. The settings

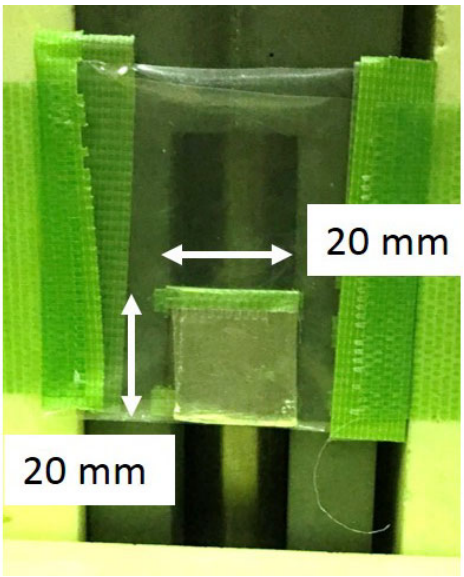
in this experiment serve as the default condition and will be the reference for the next TOF measurement experiments using sample materials.

4. Neutron Resonance Transmission Experiment

The next experiment involved testing the feasibility of the proposed system for NRTA. Through TOF measurement, the identified resonance peak in the experimental data can be used to identify the isotopes contained within the sample material. For safety reasons, instead of nuclear debris, this experiment used non-radioactive dummy materials as samples. These dummy samples have neutron energy absorption value similar to that of ^{238}U and ^{240}Pu. The configuration of the sample and its size is shown in Fig. 11.



(a) sheet-shaped sample with 0.6 mm thickness (covers whole detector area)



(b) Block-shaped sample, with 1.2 mm thickness (smallest sample size)

Fig. 11. Images of neutron detector and sample setup for short-distance NRTA experiment. (a) sheet-shaped sample with 0.6 mm thickness (covers whole detector area) and (b) Block-shaped sample, with 1.2 mm thickness (smallest sample size).

The materials for the isotope detection experiment are pure metal plate samples of indium and tungsten. They were chosen because their isotopes have relatively low neutron absorption energy with a high cross-section value according to the reference from JENDL. Therefore, the resonance peaks would be easier to observe within this compact neutron source energy spectrum. Indium has neutron resonance value close to that of plutonium isotopes between the range of 0.1–5 eV in the neutron energy spectrum, and tungsten to that of uranium isotopes between the range of 6–50 eV. The plate-shaped samples with thickness of 0.1 mm each were located in front of the ^{3}He detector, and since the sample is larger than the detector window, the effective detection area would be 20×80 mm^2. Three plates of indium and tungsten each were stacked alternately together to form a total plate thickness of 0.6 mm where indium was exposed by neutrons first and tungsten last. The obtained neutron spectrum for the mixed sample measurement is shown in Fig. 12.

The detected neutron spectrum shows several resonance peaks of different energies that correspond to different isotope materials that are sufficiently distinguished from each other to be used for identification of the materials in the sample. The value of the resonance peaks matches the references from JENDL for the isotopes ^{115}In (1.37 eV and 3.55 eV) and ^{186}W (14.2 eV), indicating that this system is able to detect several different isotopes in a mixed sample simultaneously. This measurement result satisfies the condition where there are distinguishable resonances peak in the 0.1–5 eV range and in the 6–50 eV range, which represents plutonium and uranium isotopes area, respectively. It also shows that the system will be able to identify whether the detected resonance peak belongs to plutonium or uranium isotopes in a one-time measurement.

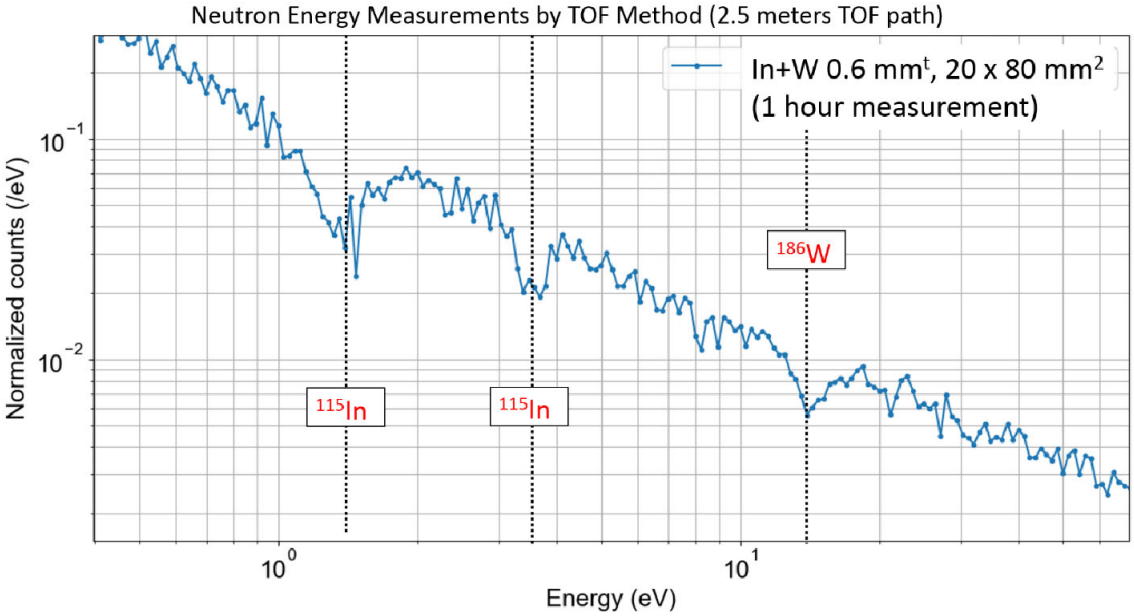


Fig. 12. Neutron energy spectrum obtained from measurement of indium and tungsten mixed plate sample with 0.6 mm thickness and 20×80 mm^2 detection area. Multiple energy resonance peaks of the respective material in the sample can be observed.

The energy resolution ($\Delta E/E$) of a TOF system is related to the time resolution (overall time dispersion divided by flight path lengths), which can be calculated using Eq. (1).

$$\frac{\Delta E}{E} = \frac{2}{L}\sqrt{\frac{E}{\alpha^2}\Delta T^2 + \Delta L^2} \tag{1}$$

In Eq. (1), L is the flight path length, and ΔL is flight path uncertainty, calculated as shown in Eq. (2), where h is half of the detector's length.

$$\Delta L = \sqrt{L^2 + h^2} - L \tag{2}$$

ΔT is the TOF uncertainty, which in this case is significantly affected by the LINAC pulse width, and α is 72.3 μs, which is the time of flight of a 1 eV neutron to cover a distance of 1 meter [13]. Table 2 shows the calculated energy resolution for this short-distance TOF system. For the three points of neutron energy of interest where the neutron absorptions happen and resonance peaks were formed, the energy resolution is within 3~10%. Compared to the large TOF facility with a long flight path and a neutron source pulse width of 1 ns with the energy resolution value of 1% [14], our system's energy resolution seems reasonable, and corresponding isotopes' resonance peak can still be distinguished by visual observation of the plot.

As a system that uses neutron TOF measurement, with its compactness and mobility, this X-band electron LINAC-based neutron source would be the most advantageous and optimum device to be implemented in an on-site screening system of plutonium and uranium inside nuclear debris.

Table 2. Energy resolution calculation of the compact TOF system with ^{3}He proportional counter.

Neutron energy of interest (eV)	Pulse width (μs)	L (m)	h (m)	ΔT (μs)	ΔL (m)	$\Delta E/E$
1.37	2.5	2.5	0.015	2.5	3.05×10^{-2}	3.24%
3.55	2.5	2.5	0.015	2.5	3.05×10^{-2}	5.21%
14.20	2.5	2.5	0.015	2.5	3.05×10^{-2}	10.42%

To determine whether the resonance peaks can still be observed when the sample is smaller than the detection area and closer to solid block rather than sheet samples, measurements using different sample size and thickness were used. By gradually decreasing the size and increasing the thickness and perform 1-hour NRTA on each of them, the minimum size and weight of the measurable samples by using 3.95 MeV X-band electron LINAC-based pulsed neutron source system can be determined as well. Figure 13 shows the plot of the neutron TOF measurement by using the smallest sample size possible, which is 20×20 mm^2 and 1.2 mm thickness, measured for 2 hours to lessen the fluctuation in the neutron counts especially in the uranium and plutonium isotopes resonance peak area.

In order to let the system to measure smaller fuel debris of a few mm solid, we have to increase the neutron intensity. For the improvement of neutron source's intensity, several methods as neutron target (beryllium) size modification, shorter neutron source's pulse width, and LINAC power capacity increase are possible, which contribute to the increase of below ten. If we keep only the compactness of system, 35 MeV X-band LINAC neutron source with 1 klystron unit of 8×10^{11} n/s is promising [15]. Based on our detection of 20×20 mm^2 and 1.2 mm thick sample for 2 hours, the above intensity enhancement of the four order (3.86×10^7 to 8×10^{11} n/s) enables detection of U and Pu in a few mm fuel debris within order of ten seconds.

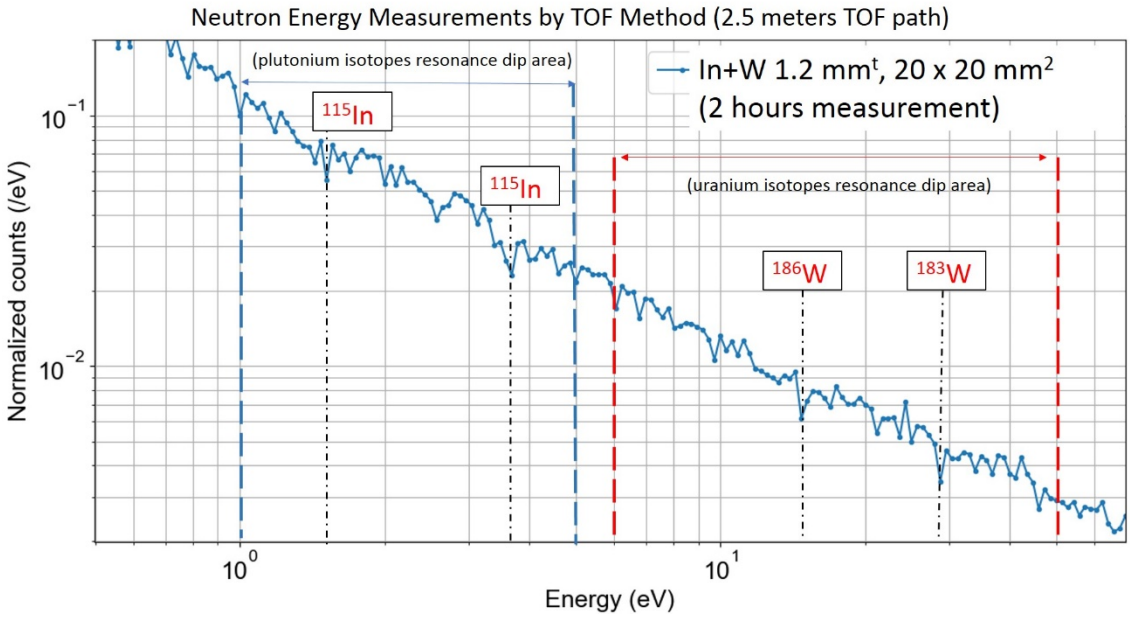


Fig. 13. Neutron energy spectrum obtained from measurement of indium and tungsten mixed plate sample with 1.2 mm thickness and 20 × 20 mm^2 detection area. The resonances formed within the respective isotopes resonance peak area determined from the simulation result can be observed.

5. Compact and mobile X-ray source using X-band electron LINAC

In the past research, application of mobile X-band electron LINAC-based X-ray source has been developed for on-site non-destructive inspection of infrastructure. As a substitute for the conventional 300 keV X-ray tube assembly NDT system that needs a long measurement time to get X-ray radiographic image, a portable high intensity X-band LINAC-based X-ray source to inspect a PC bridge inner wire condition was developed. The electron LINAC operating with an X-band frequency can cause electrons to reach a high energy within a short distance owing to its high acceleration frequency, leading to a compact system that can reach higher energies compared to conventional X-ray sources. Figure 14 shows the photo of upgraded 950 keV X-band electron LINAC-based X-ray source system. The upgraded side-coupled 950 keV system can provide X-ray intensity of almost design value (0.05 Gy/min at 1 meter) at 2.5 μsec RF pulse and 330 pulse per second (pps) [10]. This system has also been registered at local agency of labor supervision to comply within Regulations on Prevention of Ionizing Hazard, allowing the external use of this X-ray source as the energy is below 1 MeV.

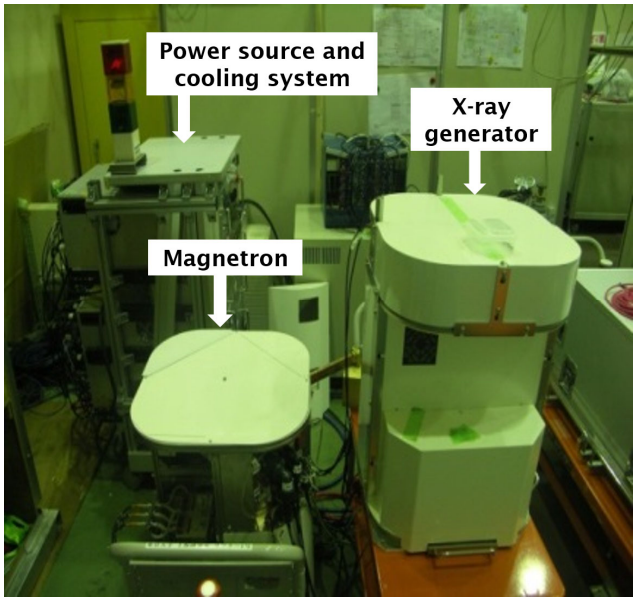
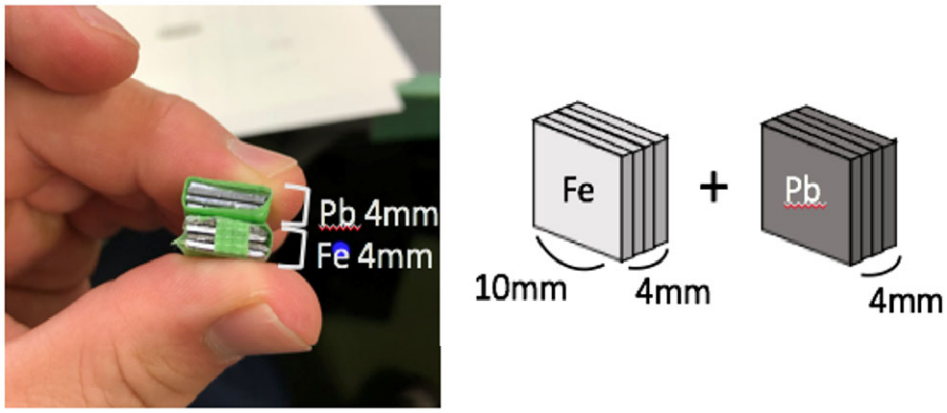


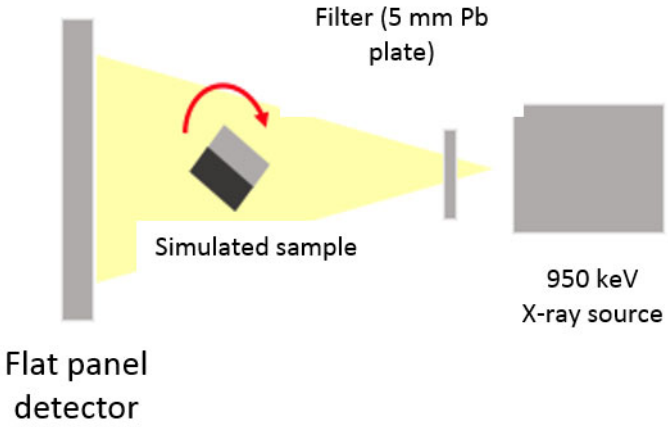
Fig. 14. Upgraded 950 keV X-band electron LINAC system.

The principle of X-ray imaging and atomic number (Z) identification is through the measurement of linear attenuation coefficient (μ) of the corresponding elements. The larger the Z of an element, the higher the μ value will be. By using polychromatic X-ray source generated through 950 keV X-band LINAC, imaging of the sample as well as measurement of its μ value can be performed, obtaining necessary data for Z identification of the elements contained in the nuclear debris. Figure 15 shows the schematic for the X-ray CT reconstruction experiment using nuclear debris dummy sample consists of Fe and Pb, and 5 mm Pb plate as X-ray filters to eliminate the beam hardening effect. In this experiment, Pb was used to model U and Pu as material with high number of Z. The spatial resolution of our X-ray CT reconstruction is 1 mm according to the result from this system's previous application for bridge inspection [10][16].

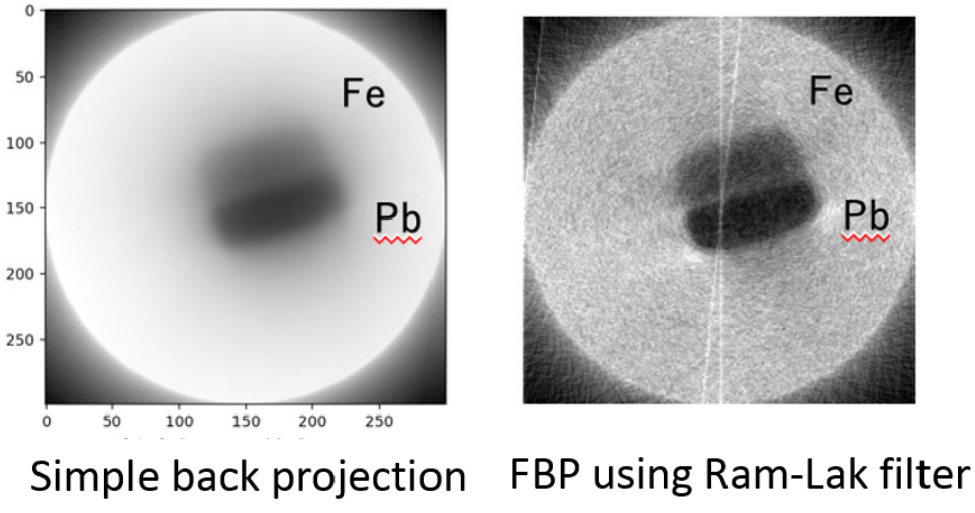
Figure 16 shows the plot of attenuation coefficient ratio of measurement result with 950 keV X-ray source to one with 3.95 MeV, for different thickness of Fe and Pb samples. It is clear the ratio is rather insensitive for the sample thickness. The imaging result, which also shows a high contrast between the materials with large gap of Z value, will be able to provide data of the corresponding material's size and weight inside the nuclear debris necessary for criticality calculation. As a proof-of-principle, this result proves that the 950 keV X-band electron LINAC-based polychromatic X-ray source can be used for atomic number identification of the material inside nuclear debris, especially in distinguishing uranium and plutonium with heavy Z from other material inside nuclear debris with lighter Z (zirconium, SUS, etc.). If a preliminarily stack database on correlation of attenuation constants and elements measured by both X-ray CT and NRTA were made, U and Pu can be identified. By combining 3D X-ray CT reconstruction results with the resolutions of 1 mm and ~100 mg, the density of U and Pu can be estimated for criticality safety evaluation.



(a) Model sample with Pb and Fe, where Pb simulates U/Pu elements (heavy Z)



(b) Schematic of CT imaging in full cycle while rotating the sample twice



(c) Cross-section of the image reconstruction of the model sample

Fig. 15. Images related to the X-ray CT reconstruction experiment using nuclear debris dummy sample. (a) Model sample with Pb and Fe, where Pb simulates U/Pu elements (heavy Z), (b) Schematic of CT imaging in full cycle while rotating the sample twice, and (c) Cross-section of the image reconstruction of the model sample.

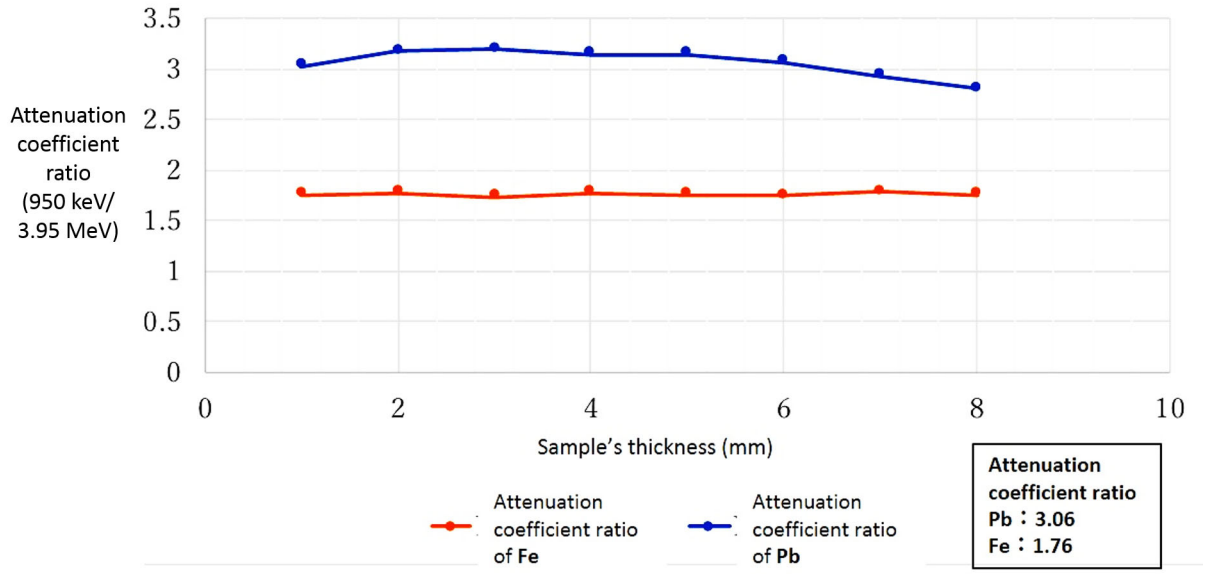


Fig. 16. Plots of attenuation coefficient ratio, calculated from measurement result with 950 keV X-ray source to one with 3.95 MeV for Fe and Pb sample with different thickness.

6. Proposal of practical system for fuel debris mass extraction and criticality safety

The main objective of this research is to make a meaningful contribution to criticality calculations for nuclear debris containers, via the determination of uranium and plutonium material density. Short-distance NRTA will complement X-ray CT system used to study nuclear debris, whereby this measurement method combination can be used to estimate the size and weight of the uranium and plutonium content in the debris, which is necessary for material density calculation. Due to its limited sample shape for measurement and long measuring time, for the consideration of practical use of the screening system, this short-distance NRTA will be used at the test extraction step for the purpose of system calibration, as shown by the scheme in Fig. 17. When mass extraction of nuclear debris happens, the actual screening process will be conducted by a fast line detector system by polychromatic X-ray CT of partial angle and parallel motion that is able to do the measurement faster for several nuclear debris samples.

Concerning the gamma rays emitted by the nuclear debris, since its energy would be very high (several hundred keV ~ several MeV) that it almost matches X-ray sources' energy, methods to reduce it will need further evaluation. Using higher energy X-ray source can cause beam hardening and makes material estimation difficult. On the other hand, shielding around the sample cannot be too heavy that it would stop X-rays from the source itself and worsen the S/N ratio. Therefore, one of the plausible solutions is to optimize the use of small debris sample and intense X-ray source.

Figure 18 shows the schematic of the line detector system and how it contributes in the criticality estimation before proceeding to nuclear debris storage. In the current stage of development, artificial elongation of reconstructed image happens due to the partial angle CT. This error has been evaluated for the X-ray bridge inspection and the diameter of reinforced iron wires and rods can be estimated with the spatial resolution of 1 mm [10][16]. The same treatment is planned to be introduced for the next step of development for the practical design.

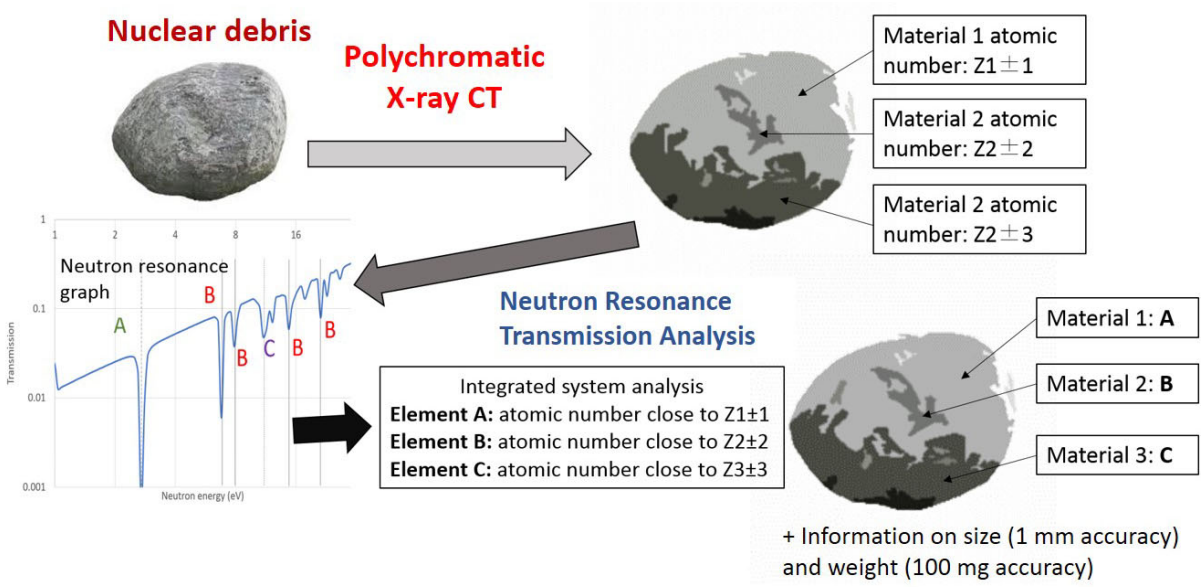


Fig. 17. Schematic of the practical combined use between X-ray and neutron method in the preparation of nuclear debris screening system.

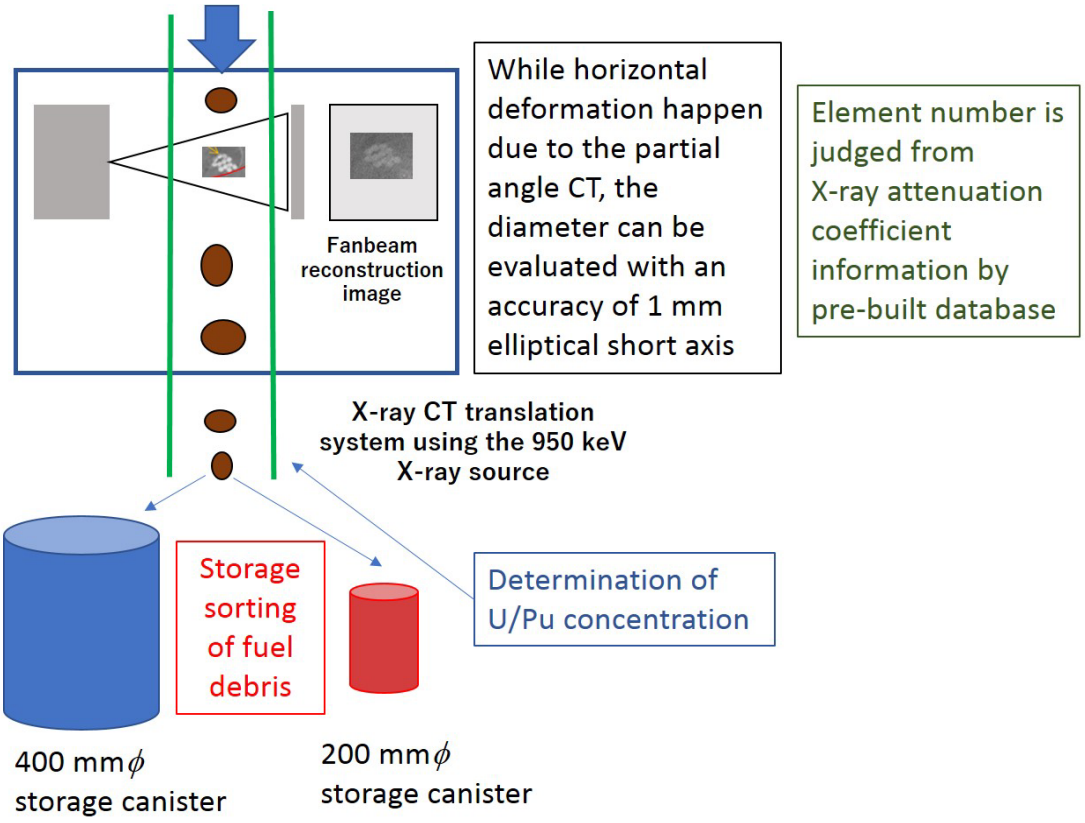


Fig. 18. Schematic of the rapid line detector system for actual nuclear debris screening system and nuclear debris storage.

7. Conclusion

We have succeeded in making the proof of principle of short-distance NRTA system using compact pulsed neutron source for the application of on-site nuclear debris screening, supported by the experiment results so far. A compact pulsed neutron source with high mobility can be constructed

from an X-band electron LINAC coupled with photon and neutron converters. From the experimental result using a 3.95 MeV X-band electron LINAC with tungsten as the photon converter and beryllium as neutron converter, a neutron TOF energy spectrum up to 70 eV can be measured within 2.5-m TOF path, with energy resolution of 4%. This system has also successfully been used to perform NRTA to simultaneously detect neutron resonance peaks in the energy range up to 30 eV for multiple elements within a sample. Based on the experiment result, it can be concluded that in principle, the short-distance NRTA system using a 3.95 MeV X-band electron LINAC-based compact neutron source would be able to confirm the existence of uranium and plutonium isotopes in a nuclear debris sample. With its compact size, mobility, and adequate level of accuracy for screening purposes, X-band electron LINAC-based compact neutron source can be implemented in an on-site screening system. It will be able to obtain nuclear debris composition data necessary for nuclear debris activity mapping of The 1F reactor core area, as a complementary in the calibration system for practical application of portable line detector X-ray CT. We are going to propose more concrete and practical system for the purpose.

For the improvement of neutron source's intensity, further optimization of the 3.95 MeV system is needed and even future development of 35 MeV system can be discussed. Aside from the on-site nuclear debris screening, this compact and mobile uranium and plutonium detection system also has potential for non-destructive analysis use in other field, such as nuclear security to prevent terrorism act.

Acknowledgement

This work was supported by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) and Japan-UK collaboration with Japan Atomic Energy Agency (JAEA), The University of Sheffield and The University of Bristol.

References

[1] M. Saeki, A. Iwanade, C. Ito, I. Wakaida, B. Thornton, T. Sakka, H. Ohba: "Development of a fiber-coupled laser-induced breakdown spectroscopy instrument for analysis of underwater debris in a nuclear reactor core." J. Nucl. Sci. Technol., Vol. 51, No. 7-8, pp. 930-938 (2014).

[2] International Research Institute for Nuclear Decommissioning: "Development of Technology for Fuel Debris Analysis/Fuel Debris Characterization." Annual Research Report 2017, IRID, Japan (2018).

[3] The Robotics Society of Japan. "Robot technology competition for nuclear reactor decommissioning." (2017). http://www.rsj.or.jp/databox/committees/dec/20160907/Decomm_koubo_jishi.pdf (Accessed March 9, 2018).

[4] L. De Chiffre, S. Carmignato, J-P. Kruth, R. Schmitt, A. Weckenmann: "Industrial applications of computed tomography." CIRP Annals-Manufacturing Technology, Vol. 63, No. 2, pp. 655-677 (2014).

[5] A. Ohzu, M. Komeda, M. Kureta, N. Zaima, Y. Nakatsuka, S. Nakashima: "Development of non-destructive assay system using fast neutron direct interrogation method for actual uranium waste drums." Nippon Genshiryoku Gakkai Wabun Ronbunshi, Vol. 15, No. 2, pp. 115-127 (2016).

[6] Kawano, S., Hayashi, T., Morishima, Y., Takahashi, Y., Toyohara, M., Baklanov, V.V., Kolodeshnikov, A.A. and Zuev, V.A., 2017. Characterization of fuel debris by large-scale simulated debris examination for Fukushima Daiichi Nuclear Power Stations. ICAPP2017: 2017 international congress on advances in nuclear power plants; Fukui (Japan); 24-25 Apr 2017.

[7] C. Paradela, G. Alaerts, B. Becker, H. Harada, J. Heyse, F. Kitatani, M. Koizumi et al: "NRD Demonstration Experiments at GELINA." JRC Technical Report, Report EUR 27507 EN (2015).

[8] K. Shibata, O. Iwamoto, T. Nakagawa, N. Iwamoto, A. Ichihara, S. Kunieda, S. Chiba et al: "JENDL-4.0: a new library for nuclear science and engineering." J. Nucl. Sci. Technol., Vol. 48, No. 1, pp. 1-30 (2011).

[9] L. Auditore, R. C. Barna, D. De Pasquale, A. Trifiro, M. Trimarchi, A. Italiano et al: "Design of a photoneutron source based on a 5 MeV electron LINAC." Proceedings of 9th European Particle Accelerator Conference (EPAC), Lucerne, Switzerland, Jul., pp. 2347-2349 (2004).

[10] M. Uesaka, Y. Mitsuya, E. Hashimoto, K. Dobashi, R. Yano, H. Takeuchi, J. Bereder, J. Kusano, E. Tanabe, N. Maruyama, Y. Hattori, M. Takewaka, H. Ono, Y. Seki, Y. Oshima, M. Ishida: "On-site Non-destructive Inspection of the Actual Bridge using the 950 keV X-band Electron Linac X-ray Source", Journal of Disaster Research, Vol.12, No.3, pp. 578-584 (2017).

[11] J. Bereder, Y. Mitsuya, Y. Takahashi, K. Dobashi, M. Uesaka, J. Kusano, Y. Tanaka, Y. Oshima, M. Ishida: "Development of 3.95 MeV X-band linac-driven X-ray combined neutron source." IOP Publishing, Journal of Physics: Conference Series, Vol. 874, No. 1, p. 012104 (2017).
[12] M. Uesaka, et al: "Applications of X-band 950 keV and 3.95 MeV linac X-ray source for onsite inspection." Proceedings of 3rd International Particle Accelerator Conference (IPAC), New Orleans, Louisiana, May., pp. 4071-4073 (2012).
[13] A. Brusegan, G. Noguere, F. Gunsing: "The resolution function in neutron time-of-flight experiments." J. Nucl. Sci. Technol., Vol. 39, No. sup2, pp. 685-688 (2002).
[14] N. Shigyo, Y. Iwamoto, D. Satoh, H. Kitsuki, K. Ishibashi, and M. Numajiri: "Improvement of energy resolution in time-of-flight method for high energy neutron measurement." IEEE, Nuclear Science Symposium Conference Record, Vol. 1, pp. 6-215 (2000).
[15] M. Uesaka, H. Kobayashi: “Compact Neutron Sources for Energy and Security.” World Scientific, Reviews of Accelerator Science and Technology (RAST), Accelerator applications in Energy and Security, Vol. 8, pp. 181–207 (2016).
[16] M. Uesaka, Y. Mitsuya, K. Dobashi, J. Kusano, E. Yoshida, Y. Oshima, M. Ishida: "On-site Bridge Inspection by 950 keV / 3.95 MeV Portable X-band Linac X-ray Sources." Bridge Optimization - Inspection and Condition Monitoring, IntechOpen, London, ISBN 978-953-51-8054-8 (2018).