Manuscript accepted by IEEE Transactions on Nuclear Science Vol. 64, pp.1635-1640 (2017). DOI: 10.1109/TNS.2017.2652619

Nondestructive Inspection System for Special Nuclear Material Using Inertial Electrostatic Confinement Fusion Neutrons and Laser Compton Scattering Gamma-rays

H. Ohgaki, *Member, IEEE*, I. Daito, H. Zen, T. Kii, K. Masuda, T. Misawa, R. Hajima, T. Hayakawa, T. Shizuma, M. Kando, and S. Fujimoto

***Abstract*—A Neutron/Gamma-ray combined inspection system for hidden special nuclear materials (SNMs) in cargo containers has been developed under a program of Japan Science and Technology Agency in Japan. This inspection system consists of an active neutron-detection system for fast screening and a laser Compton backscattering gamma-ray source in coupling with nuclear resonance fluorescence (NRF) method for precise inspection. The inertial electrostatic confinement fusion device has been adopted as a neutron source and two neutron-detection methods, delayed neutron noise analysis method and high-energy neutron-detection method, have been developed to realize the fast screening system. The prototype system has been constructed and tested in the Reactor Research Institute, Kyoto University. For the generation of the laser Compton backscattering gamma-ray beam, a race track microtron accelerator has been used to reduce the size of the system. For the NRF measurement, an array of $LaBr_3$(Ce) scintillation detectors has been adopted to realize a low-cost detection system. The prototype of the gamma-ray system has been demonstrated in the Kansai Photon Science Institute, National Institutes for Quantum and Radiological Science and Technology. By using numerical simulations based on the data taken from these prototype systems and the inspection-flow, the system designed by this program can detect 1 kg of highly enriched ^{235}U (HEU) hidden in an empty 20-ft container within several minutes.**

***Index Terms*—nondestructive inspection system, cargo container, sea port, inertial electrostatic confinement fusion device, nuclear resonance fluorescence, laser Compton backscattering**

Paper submitted in June 24, 2016 and revised in October XX, 2016.

This work was supported by Special Coordination Funds for Promoting Science and Technology in Japan (Grant No. 066). This work was partly supported by Grants-in-Aid for Scientific Research in Japan (Grant No. 21360467).

H. Ohgaki is with Institute of Advanced Energy, Kyoto University, Uji, Kyoto 6110011, Japan (e-mail: ohgaki.hideaki.2w@kyoto-u.ac.jp).

I. Daito is with Nippon Advanced Technology Co., Ltd., Ibaraki, Osaka 5670031, Japan, on leave from Institute of Advanced Energy, Kyoto University, Uji, Kyoto 6110011, Japan (e-mail: daito.izuru@gmail.com).

H. Zen is with Institute of Advanced Energy, Kyoto University, Uji, Kyoto 6110011, Japan (e-mail: zen@iae.kyoto-u.ac.jp).

T. Kii is with Institute of Advanced Energy, Kyoto University, Uji, Kyoto 6110011, Japan (e-mail: kii@iae.kyoto-u.ac.jp).

K. Masuda is with Institute of Advanced Energy, Kyoto University, Uji, Kyoto 6110011, Japan (e-mail: masuda@iae.kyoto-u.ac.jp).

T. Misawa is with Research Reactor Institute, Kyoto University, Kumatori, Osaka 5900494, Japan (e-mail: misa@rri.kyoto-u.ac.jp,).

R. Hajima is with Quantum Beam Science Research Division, National Institutes for Quantum and Radiological Science and Technology, Tokai, Ibaraki 3191106, Japan (e-mail: hajima.ryoichi@qst.go.jp).

T. Hayakawa is with Quantum Beam Science Research Division, National Institutes for Quantum and Radiological Science and Technology, Tokai, Ibaraki 3191106, Japan (e-mail: hayakawa.takehito@qst.go.jp).

T. Shizuma is with Quantum Beam Science Research Division, National Institutes for Quantum and Radiological Science and Technology, Tokai, Ibaraki 3191106, Japan (e-mail: shizuma.toshiyuki@qst.go.jp).

M. Kando is with Quantum Beam Science Research Division, National Institutes for Quantum and Radiological Science and Technology, Kizu, Kyoto 6190215, Japan (e-mail: kando.masaki@qst.go.jp).

S. Fujimoto is with Pony Industry Ltd., Osaka, Osaka 541005, Japan (e-mail: s.fujimoto@ponyindustry.co.jp).

I. Introduction

An active nondestructive detection system for inspection of special nuclear materials (SNMs), especially focused on highly enriched ^{235}U (HEU), in containers at the sea port has been developed under a support of the "R&D Program for Implementation of Anti-Crime and Anti-Terrorism Technologies for a Safe and Secure Society" promoted by the Japan Science and Technology Agency (JST). In this program, we have proposed the Neutron/Gamma-ray combined interrogation system [1]. Figure 1 shows an overview of the proposed system. The system consists of a fast screening system by using a neutron from an inertial electrostatic confinement (IEC) device [2,3] and an isotope identification system by using nuclear resonance fluorescence (NRF) induced by laser Compton backscattered (LCS) gamma-rays [4]. Since the fast screening system could not specify the position of suspicious material with good resolution (<10 cm), we

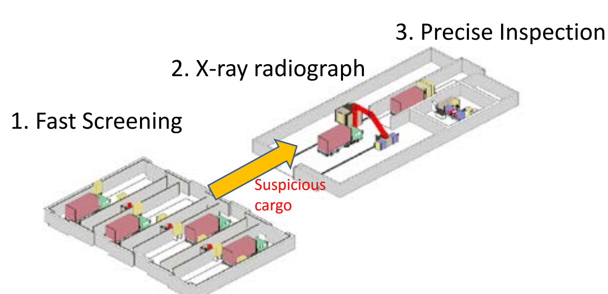

Fig. 1 Schematic drawing of the designed overall inspection system. The number of the lane of the fast screening system will be chosen by the sea port demand.

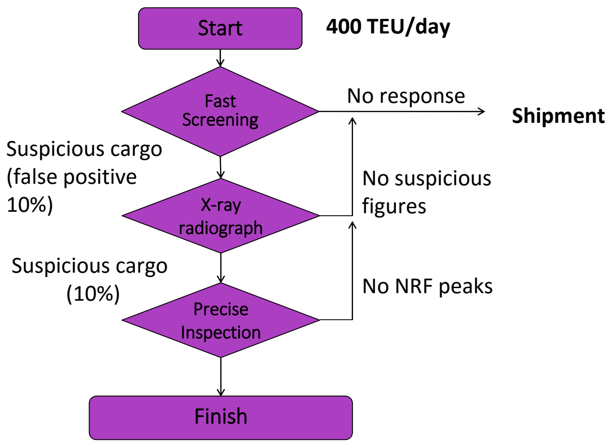

Fig. 2. Inspection-flow of the overall inspection system.

introduced an X-ray transmission radiograph system [5] to specify the suspicious position in a cargo container. The position of the LCS gamma-ray irradiation is guided to the suspicious position given by the X-ray radiograph image. In addition, the X-ray radiograph image can be used for screening of suspicious materials by its figure and density, because the false-positive events at the neutron screening system are mostly caused by low-density materials inside the cargos.

Figure 2 explains the inspection flow of the overall system. The false-positive rate is assumed as 10% in the neutron fast screening system. We also assumed that the X-ray radiograph can work for screening with a 10% false-positive rate. An engineering study to design buildings including shielding and a retracting system of container trucks has been conducted to estimate the required inspection time according to the inspection-flow.

In this paper, we describe the final design of the SNM inspection system consisting of the fast screening system by using neutrons from a D-D fusion IEC device [6] and the isotope identification system by using LCS gamma-rays from a 220-MeV microtron accelerator, which is more compact than conventional linacs. Section II briefly describes a development of the D-D fusion IEC device and two neutron-detection techniques, which are newly developed [7, 8]. The system performance was estimated by MCNP simulation [9], which was based on the experimental data taken by the prototype system. Section III describes the proof-of-principle experiment of a prototype LCS gamma-ray system driven by the existing 150 MeV microtron [10] and an array of LaBr3(Ce) scintillation detectors. The performance evaluation of the designed LCS gamma-ray inspection system driven by 220 MeV microtron accelerator [11] was examined by GEANT4 simulation [12], which used experimental data taken by the prototype and the NRF experiment on ^{235}U in the HIγS facility [13].

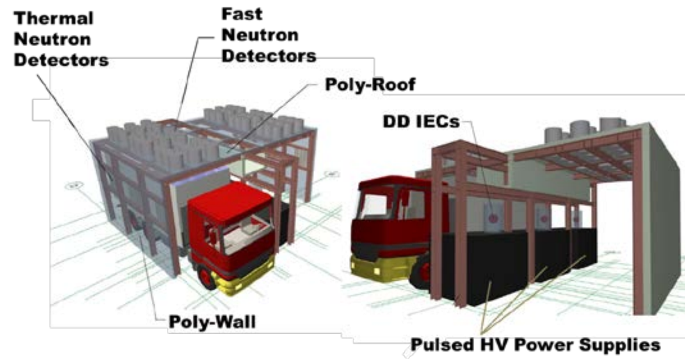

Fig. 3. Designed layout for the neutron-based fast screening system, employing three IEC-based DD neutron generators, thermal neutron detectors for the DNNA method, and fast neutron detectors for the TENA method.

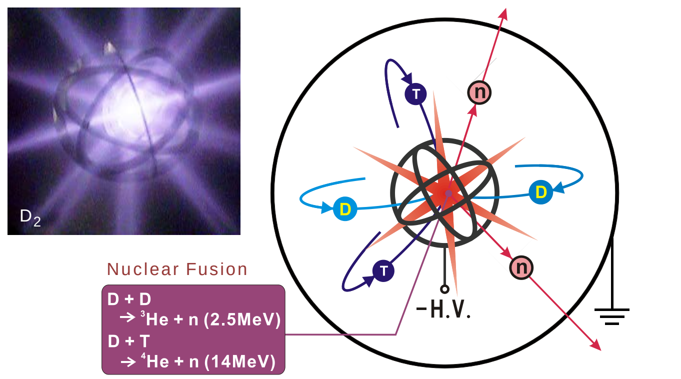

Fig. 4. Conceptual drawing of IEC device and a deuterium discharge photo [15].

II. NEUTRON-BASED FAST SCREENING SYSTEM

The neutron-based fast screening system (see Fig. 3) is required to handle hundreds of sea containers per day. If the existing neutron-detection techniques, such as Delayed Neutron Analysis [14] and Differential Die-Away Analysis [15, 16], are used for inspection systems, these systems require highly intense pulsed neutrons, e.g. 10^{11} neutrons/sec on average at the source to implement in the sea container inspection system. To obtain enough number of neutrons, D-T neutron generators have been adopted in the existing products [17]. On the other hand, D-D neutron generators have merits in safety and their easy maintenance at sea ports, which were basic requirements in the JST program. Therefore, a D-D neutron generator based on IEC of fusion plasmas with an averaged neutron flux of 10^8 neutrons/sec has been developed [6]. Besides, new neutron-measurement techniques [7, 8] suitable for D-D neutrons have been developed.

A. *IEC D-D Neutron Generator*

The IEC fusion device basically consists of a spherical-gridded cathode concentrically placed at the center of a spherical anode filled with a fuel gas (see Fig. 4). A glow discharge takes place between these electrodes. The produced ions are then accelerated toward the center through the transparent gridded cathode undergoing fusion reactions. An

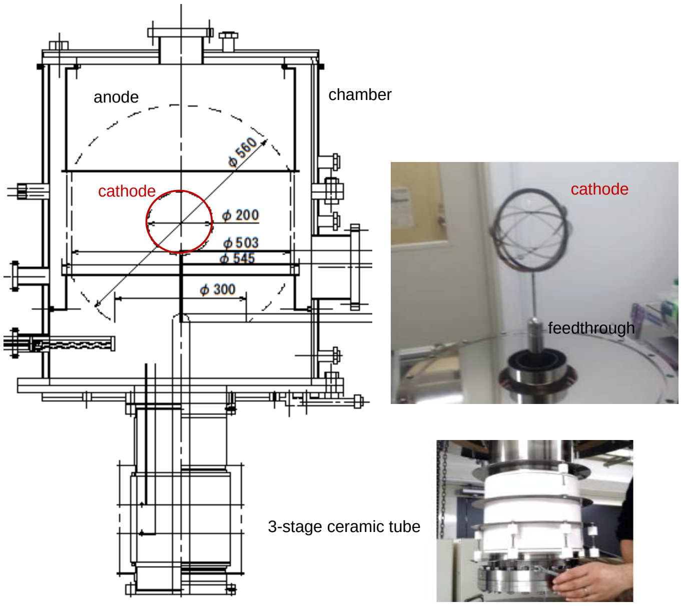

Fig. 5. The IEC neutron generator is employing 3-stage feedthrough system.

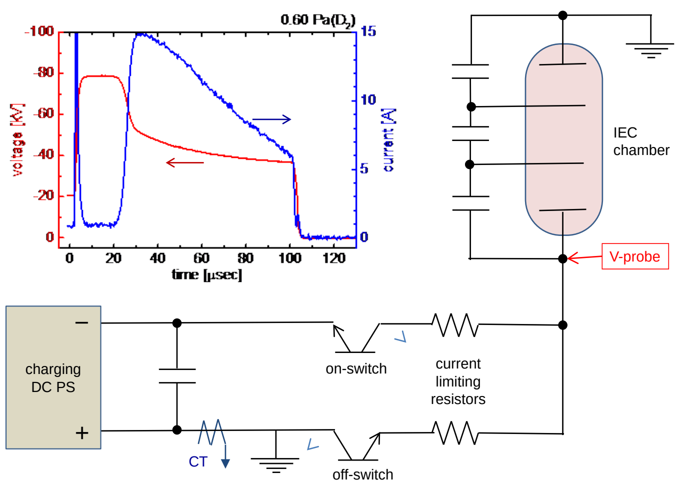

Fig. 6. The high-voltage pulsing circuit and typical pulsed waveforms of applied voltage and discharge current.

important advantage of IEC over accelerator-driven neutron generators employing solid targets comes from the use of "gas target" or "plasma target." This enables high-power operation without water-cooling of the central gridded cathode. For instance, an IEC neutron generator [18] of 20 cm in diameter demonstrated more than 6 kW discharge power to produce 10^7 neutrons/sec for D-D fusion. Both the input power and the neutron output are high in contrast with a typical commercial sealed neutron tube [19] with similar size, which generates ~10^6 neutrons/sec for D-D (~10^8 n/sec for D-T) with ~9 W. The IEC neutron generator also shows advantages of robustness and easy operation owing to its extremely simple configuration, all of which are essential for the practical uses at sea ports.

Figure 5 shows the cross-sectional drawing of the IEC neutron generator developed in the present study. Diameters of the spherical anode made of stainless steel mesh and the molybdenum-gridded cathode are 560 and 200 mm, respectively, both of which are to be placed in a cylindrical vacuum chamber of a 600 mm inner diameter. A multistage high-voltage feedthrough scheme has been developed and adopted, aiming at the capability of a high negative bias to the central cathode [20]. As a result, a D-D neutron production rate of 1.2×10^8 neutrons/sec has been achieved in a dc mode with a negative bias of 190 kV and a discharge current of 36 mA [6].

Figure 6 shows the high-voltage pulsing circuit and typical pulsed waveforms of applied voltage and discharge current. The experiments presented in the next two subsections were carried out in pulsed mode for both DNNA and TENA methods though the latter does not require pulsing of the incident neutron flux. Also, the averaged neutron yield was limited to $<10^6$ neutrons/sec, because of the radiation safety regulation in the experimental room for those experiments with ^{235}U.

B. *Delayed Neutron Noise Analysis (DNNA)*

The DNNA method is based on the variance-to-mean value method, which is one of the well-known noise analysis methods to measure the subcriticality of reactors. In this method, the variation of a neutron count rate distribution from the Poisson distribution from a target system is measured, and when the neutron count rate distribution does not show the Poisson distribution, it means the existence of fissile materials in the target system. To apply for SNM detection by using a pulse neutron source, the DNNA method was developed, where neutron count rate distributions only appeared in the delayed

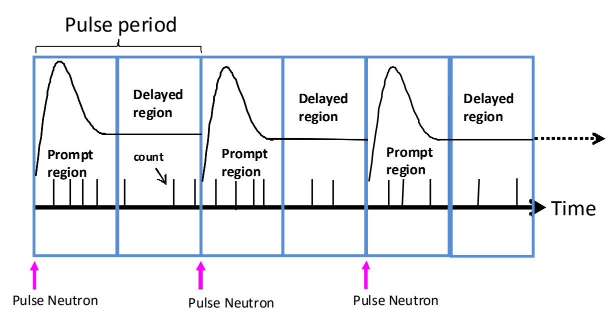

Fig. 7. Explanation of prompt region and delayed region after injection of pulsed neutron.

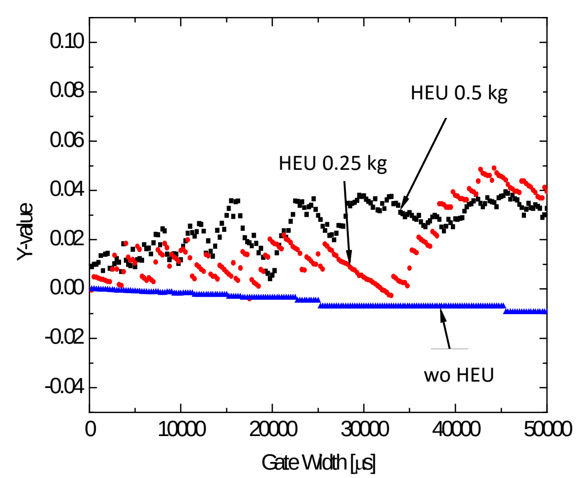

Fig. 8. A typical experimental result of DNNA method. Y-Value is Feynman Y. The vertical axis corresponds to 10-minutes measurement.

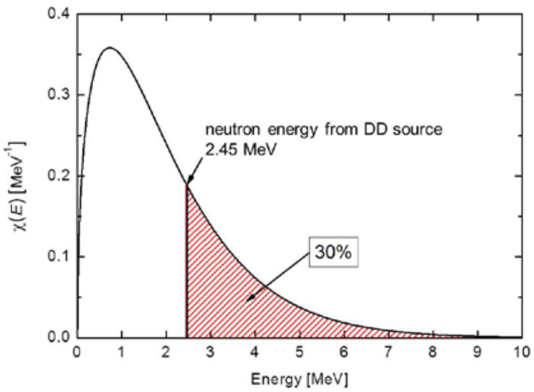

Fig. 9 Neutron energy spectrum by fission reaction. The fission neutrons above the threshold energy of 2.45 MeV from a D-D neutron source are to be detected in the present TENA method, which is indicated by the shaded area that corresponds to 30% of the total neutrons from fission reactions.

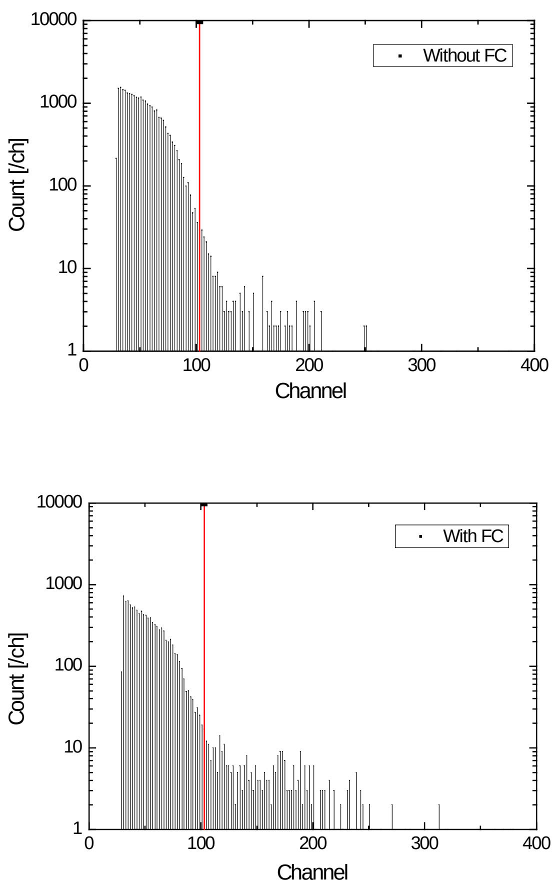

Fig. 10 A preliminary result of TENA method, which is induced by D-D neutron generator and a fission chamber target measured by liquid scintillation detector.

neutron region after the injection of pulsed neutron were analyzed to avoid difficulties caused by the dead time effect of neutron detectors as shown in Fig. 7 [7]. The validity of the present DNNA method was successfully demonstrated by experiments using an HEU and a pulse neutron generator, where ^{3}He detectors were used, the frequency of pulse neutrons was 10 Hz, and the delayed neutron region was selected as 50-100 ms after the injection of neutrons. Figure 8 shows a typical measurement result. The Y-Value of the vertical axis is Feynman Y [7]. MCNP simulations on the final design (Fig. 3) have been performed and the results show that the detection of 1 kg HEU hidden in a cargo container can be achieved by using a combination of at least three D-D pulsed neutron sources and approximately 50 neutron detectors of 1-inch diameter surrounding a cargo container within a few minutes [7].

C. Threshold Energy Neutron Analysis (TENA)

In the TENA method, neutrons from a D-D source whose energy is 2.45 MeV are injected into a suspicious target and neutron energies are measured by the surrounding neutron detectors. When SNMs exist inside an object, fission reactions are initiated by the external neutrons and they emit fission neutrons whose energies are up to approximately 10 MeV as shown in Fig. 9 [8]; therefore, the detection of neutron whose energies are higher than 2.45 MeV means the existence of SNMs in the target. The TENA method can be available only in the case of using D-D neutron sources, and not D-T neutron sources. In the test measurement with the prototype system, the neutron energies were measured by a liquid scintillation detector, which can distinguish neutron and gamma-ray by pulse shape analysis. Because of the serious SNM usage regulation, a fission chamber (FC) was used as the target. The preliminary results with and without FC are shown in Fig. 10. The red lines in the figures correspond to 2.5 MeV neutron energy. We clearly observed high-energy neutrons induced by the D-D neutron generator. We also performed MCNP simulation to estimate the inspection time of the designed system (Fig. 3), which consists of 36 liquid scintillation detectors with 3-inch diameter arranged around 20-ft cargo with 2.5-mm thickness iron wall. It should be noted that the other shielding was not arranged in the simulation. The simulation result shows that the detection of 1-kg HEU hidden in a cargo container can be achieved by TENA method with tens of detectors within 10 min of measuring time [21].

III. GAMMA-RAY INSPECTION SYSTEM

The NRF is a phenomenon in which an atomic nucleus is excited by the absorption of an incident gamma-ray whose energy corresponds to the nuclear-level energy and subsequently the excited level decays out through the emission of an NRF gamma-ray. Therefore, by measuring NRF gamma-rays, we can identify nuclear species even in hidden materials. Bertozzi et al. have proposed the novel method by application of nuclear resonance fluorescence (NRF) using gamma-rays [22]. A major challenge of implementation of the NRF method to an inspection system is to improve the signal-to-noise (S/N) ratio of the NRF measurement. Because the NRF can occur in a very narrow energy width (<< 100 eV) when compared with the irradiated gamma-rays, the rest of the incident gamma-rays are atomically scattered by irradiated materials. Therefore, Pruet et al. has proposed an inspection system based on NRF gamma-ray spectroscopy with high S/N ratios using the Thomson-Radiated Extreme X-ray Source (T-REX) [4]. T-REX can potentially generate quasi-monochromatic radiation beam using an electron linac and an intense laser system, the so-called laser Compton scattering (LCS) gamma-ray beam. However, the LCS gamma-ray beam is a low-intensity beam when compared with the conventional bremsstrahlung beam, we need a long inspection time (typically order of hours). Therefore, our proposed inspection system uses the NRF method induced by LCS gamma-ray beam for a precise inspection system by isotope identification of SNMs inside suspicious containers after passing through the fast screening system based on the D-D neutrons and the X-ray radiograph system. In this inspection-flow, we can use an enough long time, > 30 min, for the LCS gamma-ray inspection system.

A proof-of-principle (POP) experiment of the gamma-ray inspection system using NRF signal induced by LCS gamma-rays was performed at Kansai Photon Science Institute (KPSI) at QST [23]. We also examined an array of $LaBr_3$(Ce) detectors to measure the NRF gamma-rays, instead of high purity Ge detectors, which need careful treatment. LCS gamma-rays were generated by colliding Nd:YAG laser pulse (wavelength of 1064 nm, pulse duration of 200-300 ps) with 150 MeV electrons accelerated by Race Track Microtron (RTM) accelerator [24]. It should be noted that the maximum energy of the LCS gamma-ray of this POP experiment was 400 keV, which could not excite ^{235}U (1.733 MeV), we still can obtain useful information by scaling to 220 MeV microtron system [11] for actual HEU detection. To excite NRF level with 400 keV LCS gamma-rays, a natural silver block was chosen as a sample, because natural Ag consists of two isotopes, ^{107}Ag and ^{109}Ag, that have gamma-ray resonance states at 325 keV and 311 keV, respectively. Figure 11 shows the layout of the target and detectors in this POP experiment. Considering the divergence angle of the LCS gamma-rays and limited available space at KPSI, the size of the target was 40 (height) × 40 (width) × 20 (thickness) mm^3 and the target was tilted to reduce the gamma-ray attenuation in the target block. Eight $LaBr_3$(Ce) scintillation detectors with 1.5" (Dia.) × 3" (length) were positioned at 140° and 18 cm apart from the target to detect NRF gamma-rays from the target. Between the target and the detectors, a 2 mm lead plate and a 5 mm copper plate were inserted to simulate the cargo container wall. The attenuation of 300 keV gamma-ray by these plates is equivalent to that of 2 MeV gamma-ray by a 16 mm steel plate. Unfortunately, the resonant energies of Ag target were somewhat lower than the maximum energy of the LCS gamma-rays (400 keV), whereas atomic processes of gamma-ray scattering (Compton scattering, Rayleigh scattering, and so on) generated a physical background around the NRF peaks. Therefore, a tin block, which has a close atomic number and has no resonant states with excitation energies of up to 400 keV, was used as a reference target for subtraction of these background events. The repetition rate of RTM and laser pulse was set to 10 Hz and 5 Hz, respectively, to measure background events caused by neutrons and gamma-rays from the beam dump and bremsstrahlung gamma-rays generated by residual gas in the electron beam pipe. The NRF spectrum of silver target was obtained by subtraction of the Laser-OFF spectrum and the blank target (Tin) spectrum. Figure 12 shows the subtracted

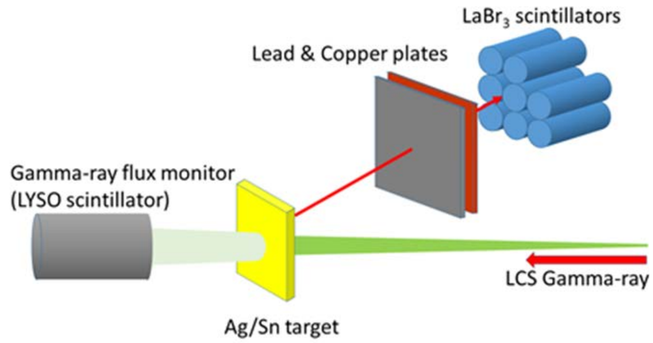

Fig.11 Layout of the target and detectors. Eight $LaBr_3$(Ce) scintillators were located at the scattering angle of 140° behind a lead and copper plate. An LYSO scintillator was used as a flux monitor of LCS gamma-rays.

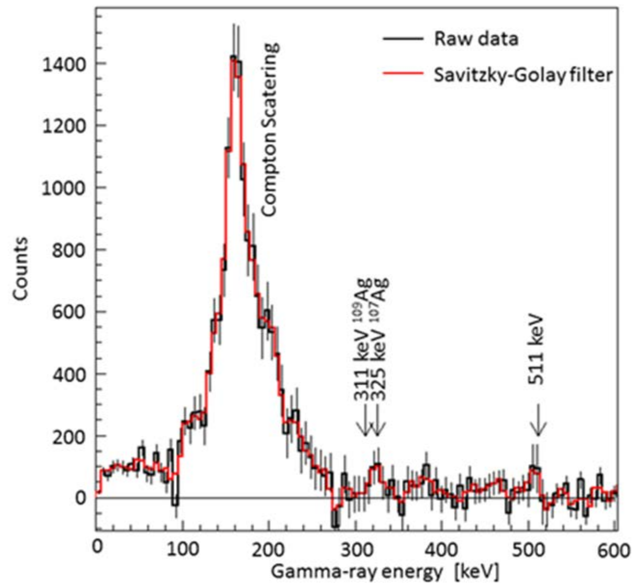

Fig. 12 Gamma-ray energy spectrum for the silver target. The black line is subtracted spectrum, and the red line is a result of smoothing by 5 terms Savitzky-Golay filter. The errors indicated in the figure are estimated only by statics.

gamma-ray spectrum. The black line is measured gamma-ray distribution from the natural silver target and the red line is a smoothed spectrum with 5-terms Savitzky-Golay filter. Error bars for statistical uncertainty, which includes errors during subtraction procedure, are also indicated. The largest peak is residual gamma-rays of Compton scattering from the target. At the energies of the NRF peaks, only one peak is observed. Because of the broad energy resolution of the $LaBr_3$(Ce) detectors (13 keV in FWHM), two NRF peaks cannot be separated. The accumulated peak count is $(2.3 \pm 1.1) \times 10^2$, which is consistent with the result of the GEANT4 simulation. The large error is originated by the background subtraction processes.

By using the GEANT4 simulation code and the above experimental data, the NRF gamma-ray yield has been calculated to a designed inspection system. We calculated that 1-kg HEU was located at the center of a 20-ft cargo with 2.5-mm thickness iron wall. Although the actual containers carry a variety of materials, we calculated an empty cargo to simplify the calculation. We should note that the demonstration experiment also assumed an empty cargo. By using a 10 x 10 array of 3.5” x 4” $LaBr_3$(Ce) detector, LCS gamma-ray flux of 10^6 photon/s with 5% energy spread, the NRF peak can be identified with a measurement time of 10 min [25]. It should be noted that the LCS gamma-ray flux was 10^5 photon/s in our POP experiment, which is 10 times smaller than the simulation condition. However, a high repetition rate, 100 Hz, microtron can be available [26]. The LCS gamma-ray flux of 10^6 photon/s could be available in the final designed system, which will use a 220 MeV 100 Hz microtron.

IV. CONCLUSION

A study on developing a nondestructive inspection system of SNMs hidden in a sea container has been promoted by the JST program. The proposed inspection system consists of a D-D neutron-based fast screening system, X-ray radiograph system, and an LCS gamma-ray-based precise inspection system. We have developed an intense IEC device to generate more than 10^8 neutrons/s by using the multistage high-voltage feedthrough structure. Two new techniques, Delayed Neutron Noise Analysis and Threshold Energy Neutron Analysis, which fit the developed D-D neutron source, have been developed. A prototype system of the neutron system was constructed at the Research Reactor Institute, Kyoto University, to evaluate the designed fast screening system. By using experimental data, MCNP simulations show that the designed system can detect 1-kg HEU in less than 10 min.

A prototype system of the LCS gamma-ray-based precise inspection system has also been constructed and tested in KPSI. An existing 150 MeV race track microtron accelerator was employed and the LCS gamma-ray of maximum energy of 400 keV with more than 10^5 photons/sec has been generated and used to irradiate a natural silver target through lead and copper plates, which simulated a shielded SNM. As a result, eight $LaBr_3$(Ce) detectors successfully detected the NRF gamma-rays from the silver target. GEANT4 simulation has also been carried out to evaluate the detection performance of the designed precise inspection system. The result showed that the designed system can detect 1-kg HEU in an inspection time of 10 min by using the LCS gamma-ray flux of 10^6 photon/s.

The overall system including inspection buildings has been designed to evaluate the required inspection time and the land space. A cargo container translation and a positioning system were also designed to estimate the total performance of the overall system. According to the inspection flow, the inspection time was evaluated and the designed inspection system, Neutron/Gamma-ray combined interrogation system, can detect 1-kg HEU located at the center of a 20-ft container within 10 min inspection time, which will be varied with the container loadings and a real-scale prototype system should be examined.

REFERENCES

[1] H. Ohgaki, T. Kii, K. Masuda, T. Misawa, C. H. Pyeon, R. Hajima, T. Hayakawa, T. Shizuma, K. Kawase, M. Kando, H. Toyokawa, “Conceptual design of a nuclear material detection system based on the neutron / gamma-ray hybrid approach”, Proceedings of IEEE International Conference on Technologies for Homeland Security 2010, pp. 525-529 (2010).

[2] G. H. Miley, L. Wu, H. J. Kim, “IEC-based neutron generator for security inspection system”, J. Radioanalytical Nucl. Chem. 263 (2005) 159-164.

[3] R. L. Hirsch, “Inertial-electrostatic confinement of ionized fusion gases”, Journal of Applied Physics 38, 4522- 4534 (1967).

[4] J. Pruet, D. P. McNabb, C. A. Hagmann, F. V. Hartemann, and C. P. J. Barty, “Detecting clandestine material with nuclear resonance fluorescence”, J. Appl. Phys. 99, 123102 (2006).

[5] i.e. http://www.as-e.com/products_solutions/omniview_gantry.asp

[6] K. Masuda, K. Inoue, T. Kajiwara, R. Nakatsu, “Compact intense neutron generators based on inertial electrostatic confinement of D-D fusion plasmas”, Proc. Nuclear Physics and Gamma-ray Sources for Nuclear Security and Nonproliferation, 195-202 (2014).

[7] T. Misawa, Y. Takahashi, T. Yagi, C. H. Pyeon, M. Kimura, K. Masuda, H. Ohgaki, “Development of measurement methods for detection of special nuclear materials using D-D pulsed neutron source”, Proc. Nuclear Physics and Gamma-ray Sources for Nuclear Security and Nonproliferation, 209-215 (2014).

[8] Y. Takahashi, T. Misawa, T. Yagi, C. H. Pyeon, M. Kimura, K. Masuda, H. Ohgaki, “Active neutron-based interrogation system with D-D neutron source for detection of special nuclear materials”, Proc. Nuclear Physics and Gamma-ray Sources for Nuclear Security and Nonproliferation, 341-346 (2014).

[9] J. F. Briesmeister, editor, MCNP - A general Monte Carlo N-particle transport code, LA-13709-M, Los Alamos National Laboratory (2000).

[10] K. Kawase, M. Kando, T. Hayakawa, I. Daito, S. Kondo, T. Homma, T. Kameshima, H. Kotaki, L.-M. Chen, Y. Fukuda, A. Faenov, T. Shizuma, M. Fujiwara, S. V. Bulanov, T. Kimura, T. Tajima, “Sub-MeV tunably polarized X-ray production with laser Thomson backscattering”, Rev. Sci. Instrum. 79, 053302 (2008); K. Kawase, M. Kando, T. Hayakawa, I. Daito, S. Kondo, T. Homma, T. Kameshima, H. Kotaki, L.-M. Chen, Y. Fukuda, A. Faenov, T. Shizuma, T. Shimomura, H. Yoshida, R. Hajima, M. Fujiwara, S. V. Bulanov, T. Kimura, T. Tajima, “Development of a sub-MeV X-ray source via Compton backscattering”, Nucl. Instr. Methods Nucl. Phys. A 637, S141 (2011).

[11] R. Hajima, T. Hayakawa, T. Shizuma, C. Angell, I. Daito, M. Kando, H. Ohgaki, “Generation of laser Compton scattered gamma-rays from a 150-MeV microtron”, Proceedings of IPAC2013, 3645-3647 (2013)

[12] S. Agostinelli et al., “Geant4 – A simulation toolkit,” Nucl. Inst. Meth. Phys. Res. A, vol. 506, pp. 250-303 (2003).

[13] Mohamed Omer, H. Negm, H. Zen, T. Hori, T. Kii, K. Masuda, H. Ohgaki, R. Hajima, T. Hayakawa, I. Daito, T. Shizuma, M. Fujiwara, S. H. Park, N. Kikuzawa, G. Rusev, A. P. Tonchev, Y. K. Wu, “Active interrogation of nuclear materials using LaBr3: Ce detectors”, Energy Precedia, 34 (2013), pp. 50 – 56.

[14] R. F. Radel, G. L. Kulcinski, R. P. Ashley, J. F. Santarius, G. A. Emmert, G. R. Piefer, J. H. Sorebo, D. R. Boris, B. Egle, S. J. Zenobia, E. Alderson, D. C. Donovan, “Detection of highly enriched uranium using a pulsed D-D fusion source”, Fusion Sci. Technol. 52 (2007) 1087-1091.

[15] J. T. Caldwell, W. E. Kunz, J. D. Atencio, “Apparatus and method for quantitative assay of generic transuranic wastes from nuclear reactors”, United States Patent Application #363, 979, 1982.

[16] K. A. Jordan, T. Gozani, “Detection of 235U in hydrogenous cargo with differential die-away analysis and optimized neutron detectors”, Nucl. Instr. Meth. A 579 (2007) 388-390.

[17] http://www.euritrack.org/

[18] K. Masuda, K. Yoshikawa, T. Misawa, K. Yamauchi, Y. Takahashi, S. Shiroya, E. Hotta, M. Ohnishi, H. Osawa, “Directional detection of nitrogen and hydrogen in explosive by use of a DD-fusion-driven thermal neutron source”, Detection of Liquid Explosives and Flammable Agents in Connection with Terrorism (Springer, the Netherlands) ISBN 978-1-4020-8465-2, pp. 155-166.

[19] http://www.sodern.com/sites/en/ref/Neutron-Tube_78.html

[20] K. Masuda, Y. Yamagaki, T. Kajiwara, J. Kipritidis, “Numerical study of ion recirculation in an improved spherical inertial electrostatic confinement fusion scheme by use of a multistage high voltage feedthrough”, Fusion Sci. Technol. 60 (2011) 625-629.

[21] T. Misawa, Y. Kitamura, Y. Takahashi, K. Masuda, A. Matsuda, S. Fujimoto, "Development of portable SNMs detection system based on threshold energy neutron analysis", To be published in Proceedings of IEEE/NSS 2016, (2016).

[22] W. Bertozzi, R. J. Ledoux, “Nuclear resonance fluorescence imaging in non-intrusive cargo inspection”, Nucl. Instrum. Methods Phys. Res. B 241, 820-825 (2005).

[23] I. Daito, H. Ohgaki, M. Kando, T. Shizuma, T. Hayakawa, C. Angell, R. Hajima, “Non-destructive inspection system of nuclear materials hidden in cargo containers”, IEEE-NSS Conference Record, N09-37 (2014).

[24] R. Hajima, M. Ferdows, T. Hayakawa, T. Shizuma, M. Kando, I. Daito, H. Negm, H. Ohgaki, “Status of laser Compton scattered gamma-ray source at JAEA 150-MeV microtron”, Proceeding of The 5th International Particle Accelerator Conference (IPAC-2014), p. 1943 (2014).

[25] H. H. Negm, H. Ohgaki, I. Daito, T. Hori, T. Kii, H. Zen, R. Hajima, T. Hayakawa, T. Shizuma, S. Fujimoto, “Study on detector geometry for active non-destructive inspection system of SNMs by nuclear resonance fluorescence”, 2015 IEEE International Conference on Technologies for Homeland Security (HST), p. 1-5 (2015), DOI:10.1109/THS.2015.7225324.

[26] http://www.hsrc.hiroshima-u.ac.jp/storagering_beamlines/sr_ring.html