

## Convertible source system of thermal neutron and X-ray at Hokkaido University electron linac facility

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**Summary.** — The convertible source system for the neutron and the X-ray imagings was installed in the 45 MeV electron linear accelerator facility at Hokkaido University. The source system is very useful for a complementary imaging. The imaging measurements for a sample were performed with both beams by using a vacuum tube type image intensifier. The enhanced contrast was obtained from the dataset of the radiograms measured with the neutron and X-ray beams.

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PACS 28.20.Pr – Neutron imaging; neutron tomography.

PACS 29.25.Dz – Neutron source.

PACS 87.59.B- – Radiography.

### 1. – Introduction

Complementary usage of neutron and X-ray imaging is expected to extend the applicable fields in nondestructive radiography [1-3]. Different cross sections of object for each beam give images with different information. The conventional neutron radiography has been generally carried out at the reactor facility [4]. On the other hand, the X-ray radiography is often carried out in relatively accessible devices. Therefore, many cases of the complementary radiography take place separately in different beam lines. However, the imagings under different experimental conditions, such as the object and detector positions or the detector type, are not expedient for the reasonable comparison of their radiograms. Fortunately, at electron accelerator-based radiation sources it is possible to obtain neutrons and X-rays relatively easily. Furthermore, higher energy X-rays can be obtainable with the accelerator-based X-ray source, reaching a penetration length comparable to neutrons. Because of these advantages, an electron beam

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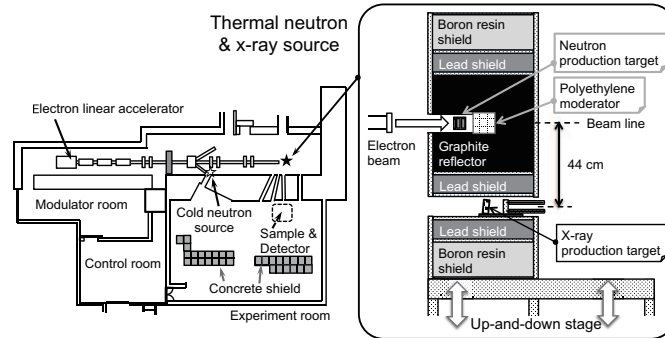


Fig. 1. – Schematic view of the electron linear accelerator facility at Hokkaido University. The inset presents the convertible source system of thermal neutron and X-ray.

accelerator-based convertible source system for neutrons and X-rays has been installed at Hokkaido University facility. In this paper, we explain about the configuration of the source system, and show the first result of the complementary radiography with this system.

## 2. – Convertible source system

A schematic view of the 45 MeV electron linear accelerator facility at Hokkaido University is shown in fig. 1. A convertible source system of thermal neutron and X-ray was newly installed on a center beam line in 2014. As shown in the inset of fig. 1, the source system mainly consists of two production targets, a polyethylene moderator, graphite reflectors, lead shield, boron-resin shields. We can choose the alternative of neutron and X-ray sources by remote control when the positions of the targets with respect to the electron beam axis are changed by moving up (or down) a stage, where the switching time is several minutes. The source system, therefore, allows us to do imaging measurements using both beams without a change of sample and detector positions.

**2.1. X-ray source.** – The cross-sectional view of the X-ray source is shown in fig. 2(a). The X-ray production target is a copper plate with a thickness of 4 mm that is tilted at  $60^\circ$

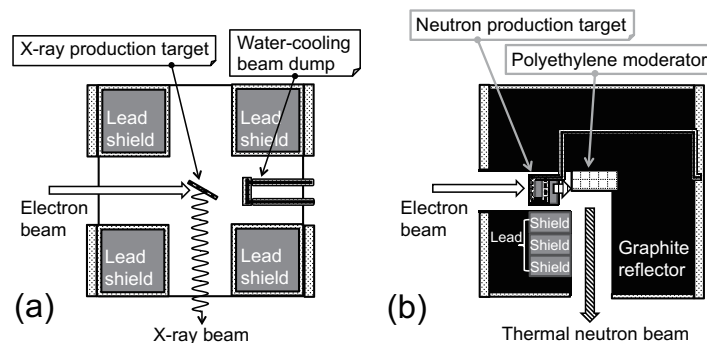


Fig. 2. – Cross-sectional views of the X-ray (a) and neutron production targets (b).

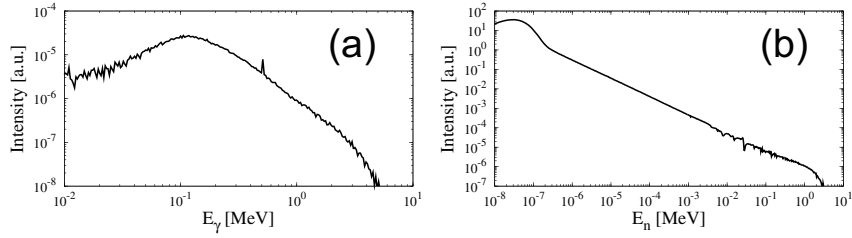


Fig. 3. – Calculated energy distributions of the X-ray (a) and neutron beams (b).

with respect to the electron beam axis. Bremsstrahlung photons are generated by hitting the copper plate with the 9 MeV electron beam and then extracted to the experimental room as the X-ray beam in the direction perpendicular to the electron beam axis. For suppressing neutron backgrounds in the X-ray beam, the energy of electron beam is set below the threshold of the  $^{63,65}\text{Cu}(\gamma, n)$  reactions. The energy distribution of the X-ray beam which was calculated with the PHITS code [5] is shown in fig. 3(a). The peak energy of the X-ray beam is estimated to be around 0.1 MeV. For the simulation, the pencil-like electron beam with a diameter of 1 cm and the energy of 9 MeV was defined as an initial source. The incident electrons induced the bremsstrahlung photons in the copper plate. The emitted photons were counted at the distance of 1 m between the electron beam axis and the tally surface.

**2.2. Thermal neutron source.** – The cross-sectional view of the thermal neutron source is shown in fig. 2(b). In the neutron production, the bremsstrahlung photon is also generated in a similar manner as the X-ray source. The higher energy electron beam, however, is used to induce the photonuclear reactions of lead isotopes by the generated photons. After the photons are generated by hitting a 4-mm-thick tungsten disc with the 34 MeV electron beam, the neutrons are produced in the thick lead blocks by the photonuclear reactions. The produced neutrons are thermalized with a polyethylene moderator (12 cm  $\times$  12 cm  $\times$  5 cm) which is surrounded graphite reflectors at room temperature. The thermalized neutrons are extracted as neutron beam through the exit aperture with an area of 10 cm  $\times$  10 cm in the perpendicular direction to the electron beam axis as shown in fig. 2(b). Three lead blocks which are mounted in the graphite reflectors are a shield to prevent the bremsstrahlung photons from entering into the neutron beam course. The energy distribution of the neutron beam, which was also calculated with the PHITS code, is shown in fig. 3(b). The distribution ranges from 0.01 eV to 10 MeV and the peak energy is 0.03 eV. A point neutron source with the Maxwell-Boltzmann distribution of  $kT = 1.3$  MeV was defined at the neutron production target as an initial source because of the computed time limitations. The thermal neutrons emitted from the moderator were counted at the distance of 1 m between the electron beam axis and the tally surface.

### 3. – Test measurements for a complementary imaging

Test measurements were performed to demonstrate a complementary imaging by using the convertible source system. A detector based on a Gd-type neutron image intensifier (TOSHIBA Ultimage<sup>TM</sup>-n $\gamma$ -04) [6, 7] was applied to the sources for the purpose of dual use, where a digital camera (CANON EOS 5D markII) was used as an image recorder.

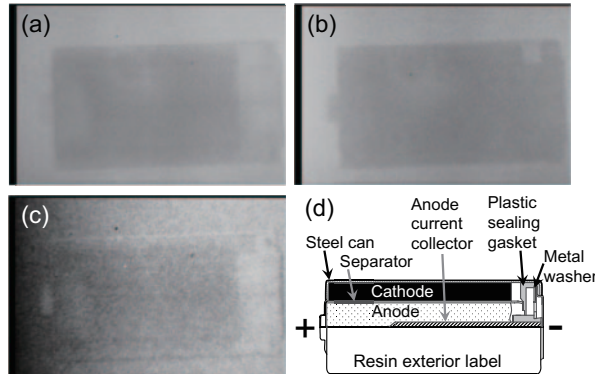


Fig. 4. – Radiography images of the C-size alkaline battery measured with the X-ray (a) and neutron beams (b). (c) shows the result which is divided the brightness value of (a) by the one of (b) at each pixel. An illustration of typical alkaline battery (d) is presented for comparison.

The distance between the source (*i.e.*, the electron beam axis) and the detector was approximately 6 m. A sample, alkaline battery, was located on the front of the input window of the detector. Each measurement time was 20 minutes.

Figures 4(a) and (b) present the images that were measured with the X-ray and neutron beams, respectively. The brightness values of the images can be directly compared owing to the complementary imaging. The result which is divided the brightness value of fig. 4(a) by the one of (b) at each pixel is shown in fig. 4(c). A difference between the images measured with the X-ray and neutron beams is clearly observed on the right side. It implicates that the substance of the portion is including hydrogen since the portion is radiopaque for neutrons and radiolucent for X-rays. For comparison, a typical alkaline battery is also illustrated in fig. 4(d). A plastic sealing gasket is generally embedded in the battery on the negative terminal side to vent interior gas pressure for safety reasons.

In the test measurements, the neutron time-of-flight (TOF) method was not applied, although the electron accelerator was operated at a repetition rate of 50 Hz and pulse width of  $3\ \mu\text{s}$ . Therefore, more detailed information about substances of a sample would be obtained from the neutron TOF images by utilizing the detector combined with other recorders such as a high-speed camera. In addition, the  $\gamma$ -flash event contaminated in the neutron beam would be distinguished.

#### 4. – Conclusion

The convertible source system for the neutron and the X-ray imagings has been installed in the 45 MeV electron linear accelerator facility at Hokkaido University. The system allows us to selectively use both beams without change of sample and detector positions. We demonstrated the test measurements to present that the convertible source system is very useful for the complementary imaging. As the results, the different images for the same sample were obtained with the neutron and X-ray beams. Moreover, the enhanced contrast could be simply obtained by comparing the brightness value of both images at the same pixel. Further work is carrying on adding the neutron TOF measurements in combination with the X-ray radiography in order to provide more detailed information about substances and structures of a sample.

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