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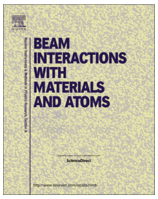

Design of an electron-accelerator-driven compact neutron source for non-destructive assay

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ABSTRACT

The threat of nuclear and radiological terrorism remains one of the greatest challenges to international security, and the threat is constantly evolving. In order to prevent nuclear terrorism, it is important to avoid unlawful import of nuclear materials, such as uranium and plutonium. Development of technologies for non-destructive measurement, detection and recognition of nuclear materials is essential for control at national borders. At Tokyo Institute of Technology, a compact neutron source system driven by an electron-accelerator has been designed for non-destructive assay (NDA). This system is composed of a combination of an S-band (2.856 GHz) RF-gun, a tungsten target to produce photons by bremsstrahlung, a beryllium target, which is suitable for use in generating neutrons because of the low threshold energy of photonuclear reactions, and a moderator to thermalize the fast neutrons. The advantage of this system can accelerate a short pulse beam with a pulse width less than 1 μs which is difficult to produce by neutron generators. The amounts of photons and neutron produced by electron beams were simulated using the Monte Carlo simulation code PHITS 2.82. When the RF-gun is operated with an average electron beam current of 0.1 mA, it is expected that the neutron intensities are 1.19×10^9 n/s and 9.94×10^9 n/s for incident electron beam energies of 5 MeV and 10 MeV, respectively.

1. Introduction

The threat of nuclear and radiological terrorism remains one of the greatest challenges to international security, and the threat is constantly evolving. In order to prevent nuclear terrorism, it is important to avoid unlawful import of nuclear materials, such as uranium and plutonium, and radioisotopes. Therefore, non-destructive measurement, detection and recognition of nuclear materials hidden cargos and containers, using radiation portal monitors and radiographic scanning systems, have been carried out for control at national borders and megaports [1–3].

Nuclide analysis of nuclear material is performed by measuring resonant scattering and fission neutrons produced by irradiating mono-energetic gamma-ray and neutron as its probe. Although a mono-energetic gamma-ray source using the laser Compton scattering method has been developed, there is a problem that the system becomes large because it requires a high energy electron beam of more than 200 MeV.

On the other hand, a neutron generator and an inertial electrostatic confinement (IEC) neutron source can remain compact by using the deuterium-tritium (DT) and deuterium-deuterium (DD) fusion reactions at low bombarding energy. Although the neutron intensity is more than 10^8 n/s in the DT reaction, the handling method of the tritium target is difficult due to its radiation control and physical properties. Therefore it is easier for the DD type without tritium, which is preferred for thermal neutron use due to the production of 2.45 MeV neutrons; however its neutron yield is small as compared with the DT type. In the case of the IEC neutron source, the neutron angular distribution is in 4π direction, when angular directivity of the neutrons is necessary, the efficiency is decreased.

There are also two typical types of accelerator-driven compact neutron source: proton-nuclear reactions using lithium or beryllium targets and photo-nuclear reactions using tantalum or lead targets. In general, although heavy metals with a large reaction cross section are adopted as the target material for photo-nuclear reactions, certain nuclei can produce neutrons at relatively low threshold energy such as 1.66 MeV for beryllium, which is around 1/4 of that for lead. The neutron production characteristics of beryllium in the case of the photo-nuclear reaction have been surveyed by Monte Carlo simulation and experiments using existing electron accelerators and their results indicated the possibility to realize a compact neutron source [4–6]. Therefore, we have been

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developing a compact neutron source using a combination of an electron accelerator and beryllium target for the non-destructive assay.

2. System configuration

2.1. Design concept

The target neutron intensity of the compact accelerator neutron source developed in this study is 10^8–10^9 n/s, which is equivalent to that of the DT neutron generators for non-destructive assay. We adopted a beryllium target with a low threshold energy of 1.66 MeV for neutron production. Although it is preferable for reduced size to use near-threshold energy, the neutron intensity is increased with incident photon energy. In order to obtain a neutron intensity of more than 10^8 n/s, an incident photon energy of at least 5 MeV is necessary according to Hawkesworth [7]. A 2.856 GHz (S-band) electron linear accelerator (linac), which is popular in industrial use, with an energy of 5–10 MeV can be fabricated with a length of 300 mm. The system configuration of the proposed electron-based accelerator and neutron production system is shown in Fig. 1.

In the case of a proton-based accelerator neutron source, the Li(p, n)Be reaction using a 2.5 MeV proton beam and the Be(p, n)B reaction using a 4 MeV proton beam are commonly used. This system can produce a neutron intensity 5–10 times larger than that of the Be(γ, n) reaction using 5 MeV photons, although the length of the accelerator system is more than 3 m. Therefore, we have been designing a 5–10 MeV electron-based accelerator neutron source using a beryllium target for downsizing.

2.2. Accelerator

We propose to use an S-band thermionic RF electron gun (RF-gun) as a compact electron linac. This photocathode type electron gun has been developed for another application and the electron beam was accelerated up to 5.5 MeV with a total gun length 245 mm [8]. However, the pulse repetition rate of the photocathode type depends on the performance of the laser irradiation system and a typical maximum rate is about 10 Hz. Therefore, a high repetition rate operation can be achieved through the use of the thermal cathode. The pulse repetition rate was assumed to be 100–500 Hz.

The RF-gun can accelerate a short pulse beam with a pulse width less than 1 μs which is difficult to produce by neutron generators. By replacing the neutron generator with our proposed neutron source, an improvement of the energy resolution of neutron time-of-flight spectroscopy is expected, contributing to an increased detection sensitivity for non-destructive assay. Furthermore, the RF-gun can produce a doubling of the electric field without changing the length of the gun by feeding about 4 times the RF power and it is therefore convenient to design a compact high energy source. The specifications of the previous photocathode RF-gun [8] and the current design are shown in Table 1.

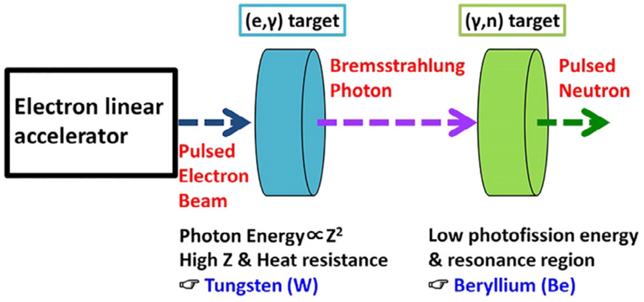

Fig. 1. The system configuration of layout of electron-based accelerator and the neutron production system.

2.3. Neutron production target

The compact accelerator neutron source developed in this study produces neutrons by the two-step reaction (e, γ)(γ, n). Firstly, the electron beam extracted from the RF-gun is irradiated to the metal target and produces photons by bremsstrahlung. Subsequently, these photons are irradiated onto the beryllium target and neutrons are produced by photo-nuclear reactions.

The energy of the photons produced by bremsstrahlung of the electron beam is proportional to the square of the atomic number of target material. Therefore, the popular heavy metal targets for photon production are uranium, platinum, tungsten and tantalum with excellent heat resistance. In this study, we used a tungsten target which is chemically stable and has a high melting point of 3380 °C, i.e. able to withstand high beam power.

Although beryllium has a low threshold energy of 1.66 MeV for the photo-nuclear reaction, it has been less likely to be used as actual targets because the neutron yield is small in the low energy region. The photo-nuclear reaction cross section of beryllium for incident photon energy has three resonance regions from the threshold energy to 3 MeV and increases sharply from around 16 MeV.

Neutrons produced from the Be target by photo-nuclear reaction contain a fast component of MeV order even though a cross section of Be(γ, n) reaction is small. Because nuclear materials such as uranium and plutonium of have large cross section for thermal/epithermal neutrons, it is necessary to thermalize the fast neutrons generated in the Be target through a moderator. We chose polyethylene which has a small atomic number and low neutron absorption as the moderator, and graphite as a reflective material of fast neutrons.

3. Monte Carlo simulations

3.1. Photon production

The amount of photons produced by bremsstrahlung reaction was estimated using the Monte Carlo simulation code PHITS 2.82 [9]. We supposed a cylindrical tungsten target with a radius of 1 cm and natural abundance ratio. Two incident electron beam energies were simulated, 5 MeV and 10 MeV. In order to simplify the estimation of neutron intensity, we assumed a point source. The relation between the thickness of the tungsten target and its photon emissions is shown in Fig. 2. The target thickness which gives the maximum photon production was 0.08 cm in the case of 5 MeV and 0.16 cm in the case of 10 MeV, respectively. When

Table 1
The specifications of the previous photocathode RF-gun and the current design.

	Previous RF-gun [8]	Current design
Cathode type	Photo cathode	Thermal cathode
Beam energy [MeV]	5.5	5.0
Electric field at the cathode surface [MV/m]	127 (simulated) 115 (measured)	125 (simulated)
Power dissipation [MW]	10	8.5
Pulse width [μs]	<2.5	<1.0
Repetition rate [Hz]	1.56	100–500
Number of resonant cavities	1.6 cell	1.6 cell
Operation mode	TM 010	TM 010

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