GENERATON OF LASER COMPTON SCATTERED GAMMA-RAYS FROM A 150-MEV MICROTRON

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Abstract

We have developed a laser Compton scattered gamma-ray source based on a 150-MeV racetrack microtron at Japan Atomic Energy Agency. The microtron equipped with a photocathode RF gun accelerates a single bunch of electrons to collide with a laser pulse from a Nd:YAG laser. We have employed laser pulse compression by stimulated Brillouin scattering to obtain high-flux gamma-rays, > 10^5 ph/s. The gamma-ray source is a prototype of commercial machine for nuclear security applications, non-destructive detection of nuclear material hidden in a ship cargo. Design and performance of the gamma-ray source are presented.

INTRODUCTION

Non-destructive inspection for screening special nuclear materials (SNM) at port-of-entries is of growing importance in view of the nuclear security, which is the detonation by terrorists of a yield-producing nuclear bomb containing fissile material. These materials such as ^{235}U or ^{239}Pu with the weights of several kilograms may be hidden in a radiation-shield box, and brought into a country using cargo containers. Finding a highly-radioactive object hidden in a cargo is possible with a conventional radiation detector. However, some kind of nuclear material, ^{235}U for example, cannot be detected by self radiation. Therefore, we need to develop a method to detect nuclear materials with an active manner based on external radiation source to trigger nuclear reactions for identifying nuclides of interest. Neutrons and γ-rays are promising incident probes for the active inspection system because of their selectivity and their high penetration.

We have proposed a SNM inspection system, which is a hybrid system of two different probes, neutrons and γ-rays as shown in Fig. 1[1]. The system consists of a fast pre-screening system by using a D-D neutron source and subsequent precise screening by using quasi-monochromatic γ-rays generated from laser Compton scattering (LCS). The pre-screening system is based on detection of delayed neutrons and neutron noise analysis method with an incident neutron probe, which is generated from D-D interaction in inertial electrostatic confinement (IEC) fusion plasmas. A prompt γ analysis is to be also used in order to maximize sensitivity of the fast pre-screening system.

If suspicious materials are detected during the fast pre-screening, the cargo is irradiated with LCS γ-rays to identify the isotope composition of the materials by using nuclear resonance fluorescence (NRF) [2].

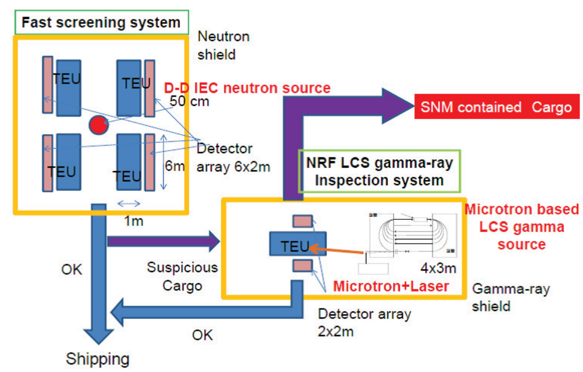

Figure 1: Conceptual design of the inspection system for nuclear material.

Since the LCS γ-ray source must be compact and easy to operate for such industrial application, we adopt a racetrack microtron for the LCS γ-ray generation. We are developing a LCS γ-ray source at the existing 150-MeV microtron of JAEA-KPSI (Kansai Photon Science Institute). The γ-ray energy available at the 150-MeV microtron with a 1 μm laser is about 0.4 MeV, which is lower than the γ-ray energy required for detecting nuclear material, 1.733 MeV for ^{235}U. Generation of high-flux γ-ray, however, can be demonstrated at the 150-MeV microtron. In the present paper, we describe the result of the γ-ray generation from the 150-MeV microtron.

LCS EXPERIMENT AT THE 150-MEV RACETRACK MICROTRON

150-MeV Racetrack Microtron

A 150-MeV racetrack microtron is installed at JAEA-KPSI, which is a commercial product of Sumitomo Heavy Industry Co. The microtron is equipped with a photocathode RF gun for single-bunch acceleration, while usual microtrons are operated in a multi-bunch mode. Figure 2 shows a schematic view of the 150-MeV microtron at JAEA Kansai. Typical operation parameters are bunch charge of 60 pC, bunch length of 10 ps (rms), normalized emittance of 35 π mm-mrad and repetition of 10 Hz [3].

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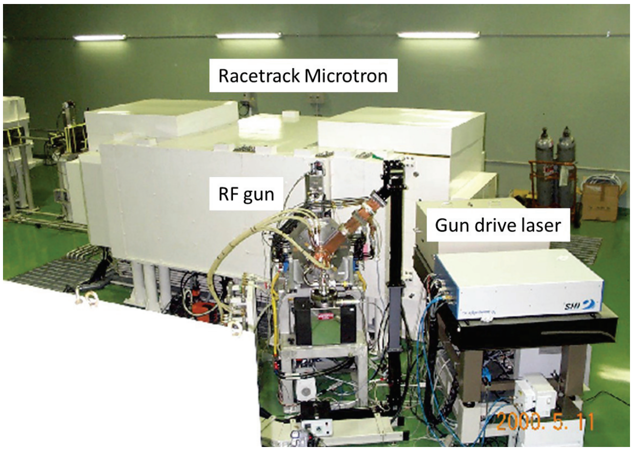

Figure 2: The 150-MeV racetrack microtron.

Laser System for γ-ray Generation

In the design of laser system for γ-ray generation, we have emphasized robustness and reliability of the laser system for the industrial usage. The laser system consists of a commercially available Nd:YAG laser (Continuum, Power Light 9010) and a pulse compressor utilizing stimulated Brillouin scattering (SBS). In our γ-ray generation, the electron laser beams collide at a small angle, 1.5 degrees, as shown in Fig.3. In this small-angle collision, the laser pulse length of YAG laser, 8 ns (FWHM), is too long to keep an efficient collision with an electron bunch [4]. Thus, we need to use a laser pulse compressor based on SBS.

Stimulated Brillouin scattering is a phenomena that an intense laser beam is back scattered with time-dependent vibration of phonon excited by the laser beam. The scattered laser beam travels in opposite direction to the incoming beam and the pulse duration of backscattered beam is determined by life time of phonon. As a result, we can compress a laser beam by choosing an appropriate material as a SBS medium.

Figure 4 shows the laser pulse compressor, which consists of two 1.5 m-long glass cells filled with Frolinate (3M, FC-40) as a SBS medium optimized for compressing a laser pulse from the Nd:YAG laser, 8 ns, to a shorter pulse, 200 ps [5].

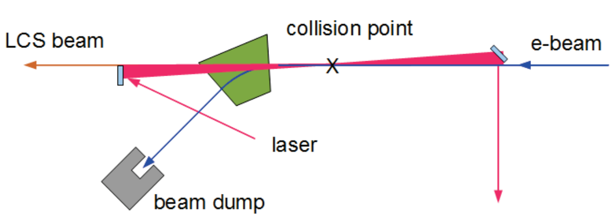

Figure 3: Layout of laser Compton scattering.

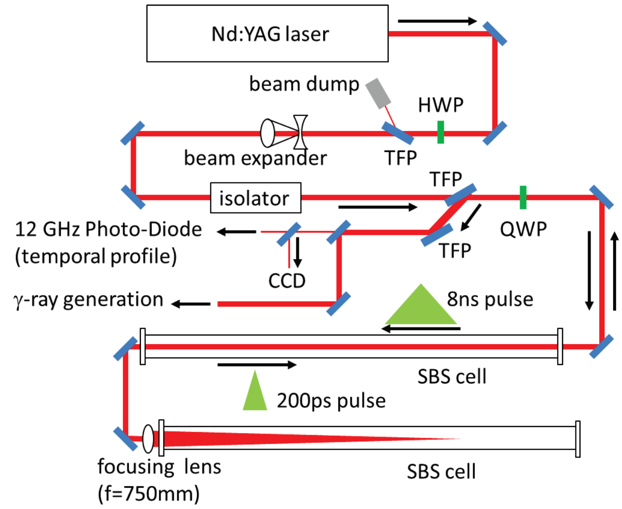

Figure 4: The laser system for γ-ray generation.

Detectors for γ-ray Measurements

In the design of nuclear material detection system installed at port-of-entries, the γ-ray source is assumed to produce γ-rays with a flux of 3x10^5 ph/s at 1.733 MeV for detecting ^{235}U. Our targeting value of γ-ray flux at the demonstration experiment, here, is 1x10^5 ph/s for 0.4 MeV γ-rays. The LCS γ-ray flux at the demonstration experiment has been evaluated by two different measurements independently. One is the direct method and the other is the scattering method.

In the direct method, total photon energy integrated over the entire γ-ray spectrum is measured by scintillation detector put on the LCS γ-ray path. The scintillation detector is a LYSO crystal (20 x 20 mm^2, 5 mm thickness) integrated with a photo-multiplier tube (PMT). Since the total photon energy of single γ-ray pulse is in the order of a few GeV, we have put a neutral density (ND) filter of appropriate thickness between the LYSO crystal and the PMT so that the output signal does not saturate. The linearity of the output signal has also been confirmed by changing the thickness of ND filter.

In the scattering method, we put an aluminium plate (3 mm thickness) at the γ-ray path with an angle of 45 degrees and measured Compton scattered photons from the aluminium plate by a GSO scintillation detector (20 x 20 x 50 mm^3).

Results of γ-ray Generation

First, the γ-ray flux measured by the two detectors have been compared with each other. With a laser pulse energy of 178 mJ, the number of γ-ray photons per pulse averaging over 3000 shots has been found to be (6.3 ± 1.5) x 10^3 ph/shot from the direct method and (5.58 ± 0.24) x 10^3 ph/shot from the scattering method [6]. These numbers are consistent with each other within an error. Figure 3 is a histogram of γ-ray photon statistics obtained from the direct method.

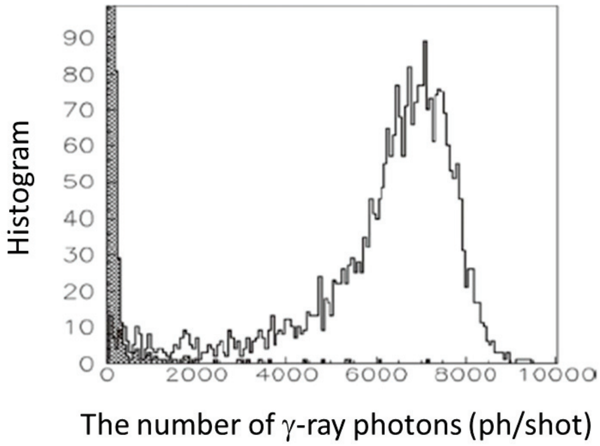

Figure 5: Histogram of γ-ray photon statistics obtained from the direct method. The number of photons per shot is $(6.3 \pm 1.5) \times 10^3$ ph/shot. The hatching area is a histogram without the laser pulse injection as a background signal.

After the calibration of γ-ray flux measurement, we increased the laser pulse energy and measured the γ-ray flux as a function of laser pulse energy. The γ-ray flux was roughly proportional to the laser pulse energy and reached to 1.2×10^4 ph/shot with the maximum laser pulse energy available in the current system, 700 mJ. This γ-ray flux corresponds to 1.2×10^5 ph/s at 10 Hz repetition, which meets the requirement of γ-ray flux for our proposing system of nuclear material detection.

FUTURE DEVELOPMENT

We plan to conduct a demonstration experiment of SNM detection by γ-ray beam from the 150-MeV microtron. Since the γ-ray energy does not cover the nuclear resonance energy of SNM, we use a substitute material having resonance energy below 0.4 MeV such as ^{107}Ag (325 keV) and ^{109}Ag (311 keV). In this experiment, nuclear resonance fluorescence from the target material is detected by an array of scintillation detector, $LaBr_3$(Ce), developed by Kyoto University [7]. The detector system has robustness and reliability necessary for industrial uses. We are also upgrading the laser system for the higher pulse energy. A new Nd:YAG laser to produce a 3 J pulse has been introduced for our future γ-ray experiments.

The final product for detecting SNM hidden in a cargo is a 1.7-MeV γ-ray source to cover a NRF energy of ^{235}U. We are designing a 220-MeV racetrack microtron in collaboration with Sumitomo Heavy Industry Co. [8]. Combining a 220-MeV electron beam and a frequency-doubled Nd:YAG laser beam, we can generate a 1.7-MeV γ-ray. Figure 6 shows a conceptual design of 1.7-MeV γ-ray source.

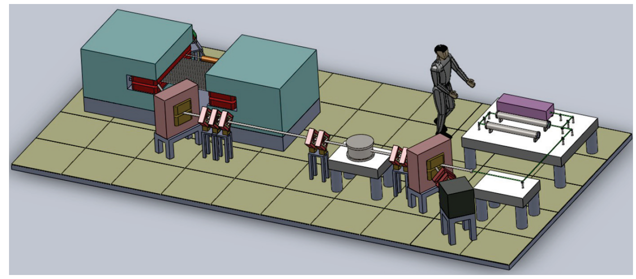

Figure 6: Conceptual design of a 1.7-MeV γ-ray source based on a 220-MeV racetrack microtron and a frequency-doubled Nd:YAG laser.

SUMMARY

In order to realize a non-destructive inspection system of nuclear materials at port-of-entries, we have developed a laser Compton scattered γ-ray source based on a 150-MeV racetrack microtron and a Nd:YAG laser at JAEA-KPSI. Using a laser pulse compressor with stimulated Brillouin scattering, we have achieved an efficient collision of the electron and laser beams to demonstrate a γ-ray flux of 1.2×10^4 ph/shot, which is equivalent to 1.2×10^5 ph/s at 10 Hz repetition. We continue to improve the γ-ray source by upgrading the laser system for a γ-ray flux of 3×10^5 ph/s.

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