COMPACT GAMMA-RAY SOURCE FOR NON-DESTRUCTIVE DETECTION OF NUCLEAR MATERIAL IN CARGO

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Abstract

A laser Compton scattered γ-ray source based on a microtron is under development for non-destructive detection of nuclear material in cargo containers. In the detection system, we employ nuclear resonance fluorescence triggered by mono-energetic γ -rays tuned at the resonance energy of nuclear material such as ^{235}U. As a prototype, a 150-MeV microtron combined with a YAG laser to produce a 400-keV γ-ray is constructed at JAEA, where critical technologies are to be demonstrated for high-flux γ -ray generation, $3x10^5$ ph/s. We also design a microtron at higher energy, 220 MeV, to produce a 1744-keV γ -ray, which is required for the detection of ^{235}U.

INTRODUCTION

Non-destructive inspection for screening special nuclear materials (SNM) at port-of-entries is of growing importance in view of the nuclear non-proliferation and counter-terrorism measures. 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. Non-destructive inspection using X-rays has been employed for the inspection. The X-rays, however, cannot distinguish isotope composition of material and cannot penetrate into a thick radiation shield. Therefore, we need to develop a new method to detect SNMs with high selectivity based on nuclear reactions to identify 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 an γ-rays [1]. The system consists of a fast pre-screening system by using a D-D neutron source and precise screening by using quasi-monochromatic γ-rays generated from laser Compton scattering (LCS). A neutron-detection scheme 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].

Since the LCS γ-ray source must be compact and easy to operate for such industrial application, we adopt a racetrack microtron to obtain high-energy electron beams. We are developing critical technologies for high-flux LCS γ-ray generation at the existing 150-MeV microtron of JAEA-Kansai. Design of 220-MeV microtron is also underway. In the present paper, we present the current status of the demo-experiment and the design study.

EXPERIMENTS AT THE 150-MEV MICROTRON AT JAEA KANSAI

150-MeV Racetrack Microtron

A 150-MeV racetrack microtron is installed at JAEA Kansai and used for studies of electron-laser interactions in vacuum and plasma. The microtron is a commercial product of Sumitomo Heavy Industry Co. and similar to one used as an injector of synchrotron light source, AURORA-2. The microtron at JAEA is designed for single-bunch acceleration, while usual microtrons are operated in a multi-bunch mode. Figure 1 shows a schematic view of the 150-MeV micrtron at JAEA Kansai. The injector is a photocathode RF gun which shares a klystron with the S-band linac of the microtron. 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].

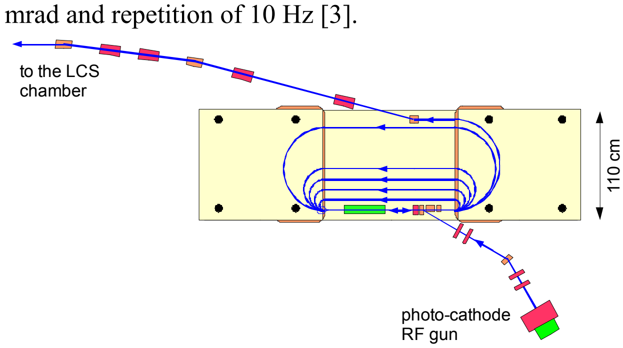

Figure 1: A schematic view of the 150-MeV racetrack microtron at JAEA Kansai.

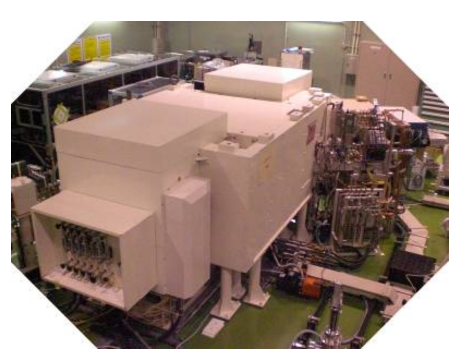

Figure 2: The 150-MeV racetrack microtron.

LCS Experiment

Generation of high-energy photons via laser Compton scattering were carried out at the 150-MeV microtron combine of a Nd:YAG laser in 2007 [4]. In the experiment, we made a collision of electron bunch with a laser pulse whose pulse energy is 0.84 J, pulse length 23 ns (FWHM) and wavelength 1064 nm. LCS photons of 20±10 photons/pulse were observed with a LYSO scintillator. The maximum energy of the LCS photon was about 400 keV. The number of LCS photon was mainly limited by small interaction of the electrons and lasers photons due to an oblique collision angle, 16º, and the relatively long laser pulse.

For the Further Increase of LCS Photon Flux

In the research program of SNM detection, we aim at generation of γ-rays at a flux of $3\text{x}10^5$ ph/s, which is larger than the previous experiment by 3 orders. For increasing the LCS photon flux, we are conducting two research items, laser pulse compression and optimization of the collision geometry. A Nd:YAG laser is suitable to obtain a laser pulse of large energy 1-10 J/pulse, but the pulse length is usually as long as 1-10 ns. This long pulse is not effective for LCS with an electron bunch of a few picoseconds.

A laser pulse can be compressed by using a pair of gratings. However, the gain bandwidth of Nd:YAG is not so wide that gratings of large dimension are necessary for the pulse compressor. Thus, we have decided to employ a pulse compression technique with stimulated Brillouin scattering (SBS). In a preliminary experiment, a laser pulse of 8.1 ns (FWHM) was compressed down to 2.1 ns (FWHM) by SBS [5]. We consider a laser pulse shorter than 1 ns can be obtained after optimization of the SBS apparatus.

The optimization of collision geometry is described in the following section.

Design of Collision Geometry

For the optimization of collision geometry, we calculate LCS photon flux in two different cases, small-angle off-axis collision and head-on collision as shown in Figure 2. The calculations have been made by Monte Carlo code, CAIN [6]. We assume electron beam parameters: energy 150 MeV, bunch charge 60 pC, bunch length 3 ps (rms), normalized emittance 30 mm-mrad, repetition 10 Hz, energy spread 0.1% (rms) and betatron function at the collision 0.25 m. Parameters of laser pulse are wavelength 1064 nm, pulse energy 1 J, repetition 10 Hz. In the off-axis collision, the collision angle is chosen at 2.5 degree.

Calculation results are shown in Fig.4, where LCS photon flux is plotted as a function of Rayleigh length. We assume laser pulse length of 100 ps and 1 ns (rms). As seen in Fig.4, the head-on collision gives the higher flux. But the off-axis collision might be a feasible choice, if the laser pulse length is 100 ps (rms). In the head-on collision, reduction of LCS photon flux due to the hourglass effect appears for a 1 ns laser pulse.

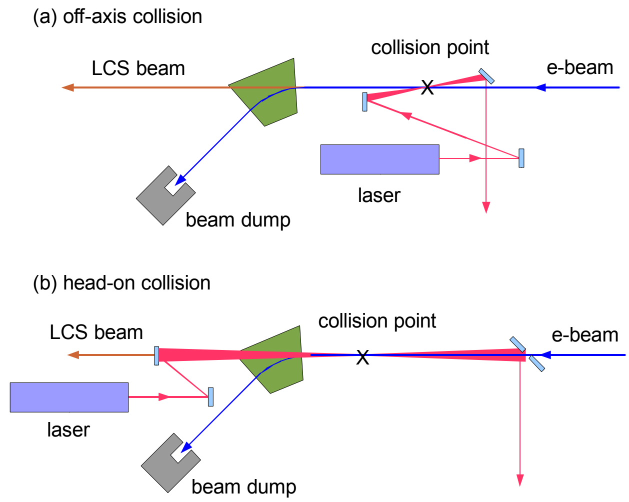

Figure 3: A schematic view of collision geometry. (a) off-axis collision and (b) head-on collision.

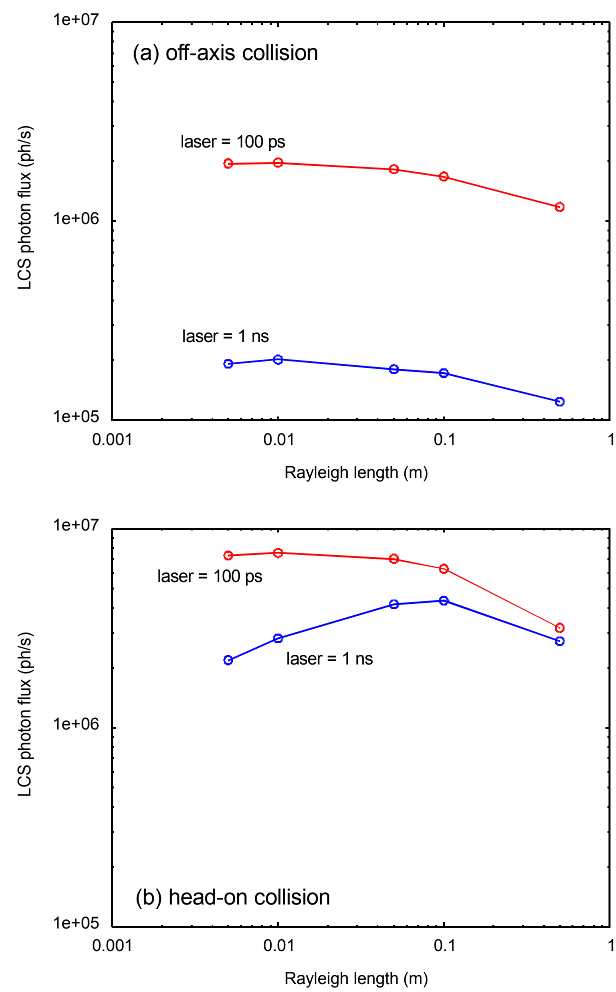

Figure 4: Calculated LCS photon flux for (a) off-axis collision and (b) head-on collision. The flux is integrated over the entire energies.

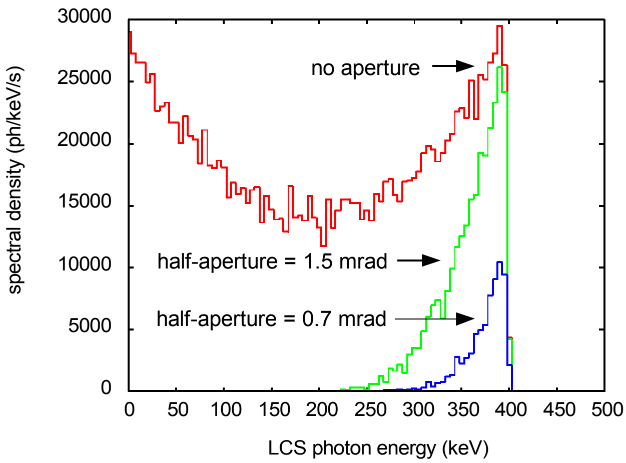

Figure 5: Calculated spectrum of LCS photons for the head-on collision with a laser pulse of 100 ps and Rayleigh length of 0.01 m.

In Figure 5, we plot energy spectra of LCS photons obtained from the Monte Carlo simulation for the head-on collision with a laser pulse of 100 ps and Rayleigh length of 0.01 m. We plot energy spectra for different size of apertures. Quasi-monochromatic γ-rays are obtained with an aperture to restrict the photon scattering angle.

DESIGN OF A 220-MEV MICROTRON

In our SNM detection system, the incident γ-ray energy must be tuned at the resonant energy of isotope to detect. We use an excitation level of 1744 keV for the detection of ^{235}U. This γ-ray energy is available from Compton backscattering of a 220-MeV electron beam and a frequency-doubled Nd:YAG laser. For the generation of high-flux γ-rays, a laser and an electron beam must be focused into a small spot size at an interaction point. For this purpose, we employ a photocathode RF gun for an injector of the 220-MeV microtron as well as the 150-MeV microtron [7].

In the design of a microtron, the following equation must be fulfilled to achieve continuous acceleration during successive turns:

$$\Delta E(\mathrm{MeV}) = \frac{\nu\lambda(\mathrm{cm})B(\mathrm{T})}{2.096},$$

where ΔE is the energy gain per turn, λ is the RF wavelength, B is the field of bending magnets and ν is an integer. In general microtrons, ν=1 is chosen, because this choice makes the longitudinal acceptance maximum. In our microtron with a photocathode RF injector, however, ν=2 is also a feasible choice, because an electron bunch from the injector is 10-20 ps and enough acceptable in a microtron of ν=2 with an S-band structure.

Table 1 shows design parameters of a 220-MeV microtron for ν=1 and ν=2 cases. We are conducting a detail design study with taking the following issues into account: transient beam loading effects in single bunch acceleration, beam dynamics in the microtron, initial and operation cost of the machine.

Table 1: Design Parameters of a 220-MeV Microtron

microtron		
ν	1	2
energy gain per turn (ΔE)	7.5 MeV	12 MeV
bending magnet field (B)	1.5 T	1.2 T
number of turns	30	19
bunch length	20 ps	10 ps
extraction energy	220 MeV	
bunch charge	500 pC	
repetition	100 Hz	
RF frequency	2856 MHz	
injector		
energy	~4 MeV	
normalized emittance	1-10 π mm-mrad	

SUMMARY

A research program to realize a non-destructive inspection of SNMs in cargo containers at port-of-entries has been established. The inspection consists of a fast pre-screening by D-D neutrons and a precise screening by LCS γ-rays. The γ-ray system can detect ^{235}U by irradiation of 1744-keV γ-rays and measurement of NRF signals. In JAEA, a compact LCS γ-ray source for the above purpose is under development, which is based on a racetrack microtron and a Nd:YAG laser. We will soon start a demo-experiment to obtain LCS γ-rays at a flux over 3×10^5 ph/s. A racetrack microtron of 220-MeV is also under designing for generating 1744 keV γ-rays.

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