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Author(s)	Zen, Heishun; Taira, Yoshitaka; Konomi, Taro; Hayakawa, Takehito; Shizuma, Toshiyuki; Yamazaki, Junichiro; Kii, Toshiteru; Toyokawa, Hiroyuki; Katoh, Masahiro; Ohgaki, Hideaki
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CoE on Sustainable Energy System (Thai-Japan), Faculty of Engineering, Rajamangala University of Technology Thanyaburi (RMUTT), Thailand

Generation of High Energy Gamma-ray by Laser Compton Scattering of 1.94-μm Fiber Laser in UVSOR-III Electron Storage Ring

Heishun Zen[a,*], Yoshitaka Taira[b], Taro Konomi[c,d], Takehito Hayakawa[e], Toshiyuki Shizuma[e], Junichiro Yamazaki[c], Toshiteru Kii[a], Hiroyuki Toyokawa[b], Masahiro Katoh[c,d], Hideaki Ohgaki[a]

[a]*Institute of Advanced Energy, Kyoto University,Uji 611-0011, Japan*
[b]*National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba 305-8568, Japan*
[c]*UVSOR Facility, Institute for Molecular Science, Okazaki 444-8585, Japan*
[d]*School of Physical Sciences, The Graduate University for Advanced Studies (SOKENDAI), Okazaki 444-8585, Japan*
[e]*Japan Atomic Energy Agency, Tokai-mura 319-1184, Japan*

Abstract

Development of a laser Compton scattering (LCS) gamma-ray source in the UVSOR-III storage ring has been proposed to perform basic research on non-destructive three dimensional isotope imaging. As the first step of the development, a numerical simulation was performed to evaluate the performance of the gamma-ray source. The expected total flux is about 1×10^7 photons/s when a 1.94-μm CW fiber laser with the maximum power of 5 W collides with 300-mA electron beam circulating in the storage ring. The maximum gamma-ray energy and the total flux available were measured in experiment and determined as 5403 ± 16 keV with 1×10^7 photons/s, respectively. The electron beam energy was evaluated as 746 ± 1 MeV from the measured maximum gamma-ray energy. From the numerical calculation and the experimental result, the energy spread of 2.9% in full width at half maximum and the flux of 4×10^5 photons/s are expected for the LCS gamma-ray beam when a collimator with 2-mm hole is used to limit the scattered angle. The quality of gamma-ray beam generated in UVSOR-III is enough to perform a basic study on the non-destructive three dimensional isotope imaging.

Keywords: Gamma-ray Source; Laser Compton Scattering; Non-destructive Three Dimensional Isotope Imaging

* Corresponding author. Tel.: +81-774-38-3424; fax: +81-774-38-3426.
E-mail address: zen@iae.kyoto-u.ac.jp

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1. INTRODUCTION

Intense gamma-rays with various excellent properties such as quasi-monochromaticity, energy tunablity, good directivity, and high polarization can be used for many applications in nuclear physics and non-destructive analysis. Such a gamma-ray can be generated by collision of an intense laser beam with a high energy electron beam. This process is known as laser Compton scattering (LCS) and generated gamma-ray is often called as LCS gamma-ray. The first demonstration experiment was performed at the Lebedev Physical Institute of the Academy of Science 600 MeV synchrotron with a ruby laser [1]. So far, the LCS gamma-rays have been generated for various application experiments in many accelerator facilities [2-9].

One of the most interesting applications with the LCS gamma-ray is the non-destructive isotope imaging by measuring nuclear resonance fluorescence (NRF) [10-12]. A demonstration of the isotope imaging has been conducted at the electron storage ring TERAS in National Institute of Advanced Industrial Science and Technology, Japan [13]. In the experiment, quasi-three dimensional distribution of ^{208}Pb was identified by measuring the amount of 5512-keV gamma-rays which were emitted from ^{208}Pb via the NRF process.

However, the TERAS facility was damaged and shut down by the Great East Japan Earthquake in 2011. We therefore proposed the development of a LCS gamma-ray source in the UVSOR-III electron storage ring [14] to promote the basic research of isotope imaging. As the first step of the development, the properties such as the maximum gamma-ray energy and the total gamma-ray flux were measured for the LCS gamma-ray source generated by using a 1.94-μm fiber laser. The results of numerical simulation and measurements are reported in this paper.

2. LASER COMPTON SCATTERING

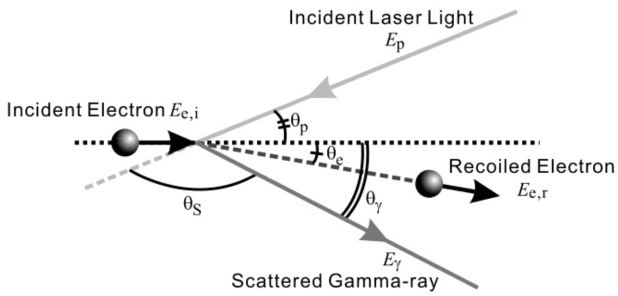

Fig.1. Schematic Diagram of the Laser Compton Scattering

The mechanism of laser Compton scattering is illustrated in Fig. 1. A laser photon with an energy of E_p collides with a relativistic electron with an initial energy of $E_{e,i}$ at an angle of θ_p. The incident photon energy is up-converted to E_γ which is expressed as [15]

$$E_\gamma = \frac{E_p(1+\beta\cos\theta_p)}{1-\beta\cos\theta_\gamma + \dfrac{E_p}{\gamma m_0 c^2}(1-\cos\theta_S)} \tag{1}$$

where m_0 is the rest mass of the electron, γ is the Lorentz factor, $\gamma = (1 - \beta^2)^{-1/2}$, $\beta = v/c$ is the electron velocity relative to the velocity of light, θ_γ is the angle of scattered gamma-ray and θ_S is the angle between the incident laser photon and the scattered gamma-ray. In case of high energy electron beam i.e., $\gamma > 1000$, and small scattering angle of $\theta_\gamma << 1$, the energy of LCS gamma-ray can be simplified as

$$E_\gamma \approx \frac{2E_p\gamma^2(1+\beta\cos\theta_p)}{1+\gamma^2\theta_\gamma^2} \tag{2}$$

For the head-on collision, $\theta_p = 0$, the gamma-ray energy can be described as

$$E_\gamma \approx \frac{4E_p\gamma^2}{1+\gamma^2\theta_\gamma^2} \tag{3}$$

The maximum gamma-ray energy can be observed at $\theta_\gamma = 0$ and given as,

$$E_{\gamma,\max} \approx 4E_p\gamma^2 \tag{4}$$

Here the energy of laser photon is up-converted to approximately $4\gamma^2$ times higher energy by colliding with high energy electrons. For example, if 1-eV laser photon collides with 500-MeV electron, gamma-ray with the maximum energy of approximately 3.84 MeV can be generated.

The scattered gamma-ray energy depends on the scattering angle θ_γ as shown in equation 3. Therefore, by defining the scattering angle, a quasi-monochromatic gamma-ray beam can be obtained.

In another view point, we can evaluate the energy of electron beam by measuring the maximum energy of scattered gamma-ray. Actually, the laser Compton scattering has been used for measuring the electron beam energy in various electron storage rings [2, 5, 16-20].

3. EXPERIMENTAL SETUP

In this section, major components used in this experiment and geometry of experiment are described.

3.1. UVSOR-III Storage Ring [14]

The UVSOR-III storage ring is a 3rd generation light source with the maximum energy of 750 MeV. The main parameters and schematic drawing are shown in Table 1 and Fig. 2, respectively. In the storage ring there are four 4-m long straight sections and four 1.5-m short straight sections. One of the long straight sections indicated by black ellipse in Fig. 2 was used for LCS gamma-ray generation experiments.

Table 1. Main Parameters of the UVSOR-III Storage Ring

Maximum Energy	750 MeV
Normal operation Current (Top-up Mode)	300 mA (multi-bunch) 50 mA (single bunch)
Natural Emittance	17.5 nm-rad
Circumference	53.2 m
RF Frequency	90.1 MHz
Harmonic Number	16
Bending Radius	2.2 m
Straight Section	(4 m × 4) + (1.5 m × 4)
Energy Spread	5.26×10^{-4}
Natural Bunch Length	128 ps

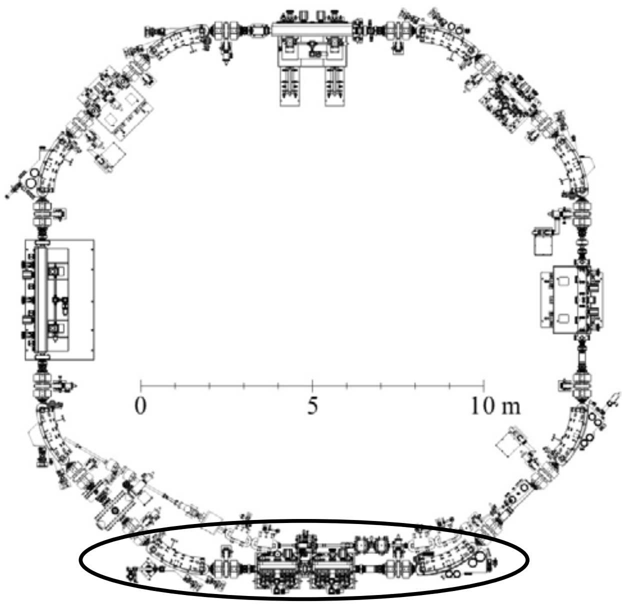

Fig.2. Schematic Diagram of UVSOR-III Storage Ring. Black Ellipse Indicates the Straight Section Used in This Research.

3.2. Fiber Laser

A 1.94-μm wavelength fiber laser was used for 5-MeV gamma-ray generation to excite levels at 5512-keV or 5292-keV in ^{208}Pb. The main specification of the fiber laser is listed in Table 2. This laser operates in CW mode with a narrow line width (< 1 nm). The maximum output power is about 5 W. The operation wavelength of the laser was determined as 1944.78 ± 0.07 nm from measurement of the wavelength spectrum by a NIR spectrometer (NIRQUEST512-2.2, Ocean Optics, Inc.).

According to the equation 4, the expected maximum energy of scattered gamma-rays is about 5.5 MeV when this laser (E_p = 0.6375 eV) is scattered by 750-MeV electron beam.

Table 2. Main Parameters of the Fiber Laser

Model Name	AP-Tm-1950-SM-05-LP
Company	AdValue Photonics Inc.
Operation Mode	CW
Operation Wavelength	1944.78 ± 0.07 nm (Energy : 0.6375 eV)
Max. Output Power	5 W
Spectral Line Width	< 1 nm
Beam Quality, M^2	< 1.1
Output Polarization	Linearly Polarized

3.3. Gamma-ray Detectors and Counting System

In this experiment, two detectors were used. One is a high purity germanium (HPGe) detector (GEM-120225-P, EG&G ORTEC) and the other is a $LaBr_3$(Ce) scintillation detector (crystal size: diameter of 38.1 mm and length of 76.2 mm, Model: 38S76, PM:R9420-100 MOD, SAINT-GOBAIN). The photograph of the HPGe detector and the

$LaBr_3(Ce)$ detector are shown in Fig. 3 (a) and (b), respectively. The HPGe detector was used for the maximum gamma-ray energy measurement and total flux measurement under low electron beam current and low laser power condition. The $LaBr_3(Ce)$ detector was used for total flux measurement under the maximum electron beam current and maximum laser power condition. A digital signal processor module (APU8008, Techno AP) was used for recording the energy spectrum.

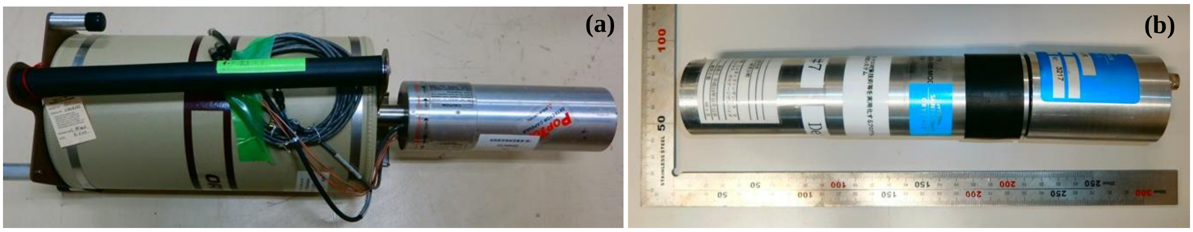

Fig.3. Photographs of (a) HPGe Detector, and (b) $LaBr_3(Ce)$ Scintillation Detector.

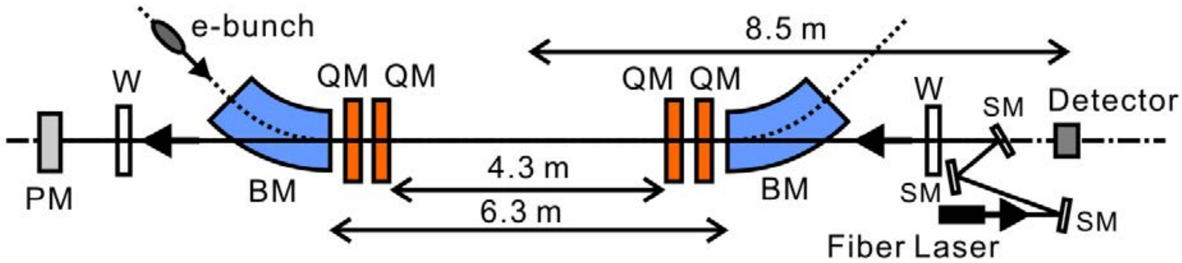

Fig.4. Schematic Diagram of Experimental Geometry. QM: Quadrupole Magnet in the Storage Ring, BM: Bending Magnet in the Storage Ring, W: Quartz Window, SM: Silver Mirror, PM: Laser Power Meter.

3.4. Geometry

The entire geometry of the present experiment is shown in Fig. 4. The 1.94-μm fiber laser beam was injected to a straight section of the UVSOR-III storage ring through a vacuum window (W) made by fused silica. The distance between two quadrupole magnets (QM) in the straight section was 4.3 m and the distance between two bending magnets (BM) was 6.3 m. The distance between the center of the straight section and the gamma-ray detector was approximately 8.5 m. The power of the transported laser beam was monitored by a laser power meter (PM) after passing through the upstream side vacuum window (W) made by fused silica.

4. EXPECTATION OF PERFORMANCE

4.1. Total Flux

Total flux of generated gamma-ray, N_γ, can be given in the formula [21],

$$N_\gamma = L\sigma(\theta_\gamma)$$
$$L = 2cfN_e\lambda_p \cos^2\left(\frac{\theta_p}{2}\right)\int_{-\infty}^{\infty} \rho_e(x,y,z,t)\rho_p(x,y,z)\mathrm{d}x\mathrm{d}y\mathrm{d}z\mathrm{d}t \tag{5}$$

where $\sigma(\theta_\gamma)$ denotes the cross section of Compton scattering in scattering angle θ_γ, L is the luminocity, f is the number of collision per unit time, N_e is the number of electron in bunch, λ_p is the line density of laser photon, ρ_e is the distribution function of electron beam and ρ_p is the distribution function of laser beam. If the electron beam and laser beam have gaussian distribution and making head-on collision in z-axis, the equation 5 can be simplified to

$$N_\gamma = \frac{fN_e \lambda_p \sigma(\theta_\gamma)}{\pi} \int_{-l/2}^{l/2} \left[\left(\sigma_{xe}^2 + \sigma_{xp}^2 \right) \left(\sigma_{ye}^2 + \sigma_{yp}^2 \right) \right]^{-\frac{1}{2}} \mathrm{d}z \tag{6}$$

where σ_{xe} and σ_{ye} denote the RMS electron beam size in horizontal and vertical direction, respectively, and σ_{xp} and σ_{yp} denote the RMS laser beam size in horizontal and vertical direction, respectively.

In the case of UVSOR-III, the number of electrons in single revolution per unit current N_e/I_e is 1.1×10^{12} A^{-1}, where I_e denotes the beam current. The collision rate or revolution frequency f is 5.635 MHz. The line density of laser photon is given by

$$\lambda_p = \frac{P}{eE_p} \frac{1}{c} \tag{7}$$

where P and e denotes the laser power and the elementary charge, respectively. The line density of laser photon per unit power is calculated as $\lambda_p/P = 3.3\times10^{10}$ m^{-1} W^{-1}. For simplicity, we assume constant electron beam size and laser beam size in the collision region, σ_{xe} = 420 μm, σ_{ye} = 15 μm, σ_{xp} = 1.5 mm, σ_{yp} = 1.5 mm. Then equation 6 can be written as

$$N_\gamma = \frac{fN_e \lambda_p \sigma(\theta_\gamma) l}{\pi} \left[\left(\sigma_{xe}^2 + \sigma_{xp}^2 \right) \left(\sigma_{ye}^2 + \sigma_{yp}^2 \right) \right]^{-\frac{1}{2}} \tag{8}$$

where l is the length of interaction region, 6.3 m in this case. In the case of the laser Compton scattering with a high energy electron, we can consider the cross section of the Compton scattering is almost equal to the cross section of the Thomson scattering, which is the low energy limit of the Compton scattering, 6.652×10^{-29} m^2. Finally the total gamma-ray flux in unit time with unit electron beam current and unit laser power is calculated as 1.1×10^7 photons s^{-1} A^{-1} W^{-1}. In the case of the maximum beam current of UVSOR-III, I_e = 300 mA, and the maximum laser power, P = 5 W, the maximum total gamma-ray flux is expected to be 1.7×10^7 photons/s. The flux can be increased by focusing the laser beam, i.e. making the laser beam size small.

4.2. Flux and Energy Spread after Collimator

As one can easily understand from equation 3, the energy of a scattered photon depends on the scattering angle θ_γ. When we define the scattered anlgle of LCS photons by a collimator, a quasi-monochromatic gamma-ray beam can be obtained. The expected gamma-ray spectra with different hole size of collimators derived by numerical simulation EGS5 [22] are shown in Fig. 5. The expected maximum gamma-ray flux and the energy spread in FWHM after a collimator are summarized in Table 3. In this calculation, the electron beam emittance, energy spread, spacial, and angular distributions are taken into account. The linewidth of the laser beam is also included in the calculation. In the UVSOR-III storage ring, we can expect generation of a high flux (> 10^5 photons/s) and narrowband (< 3%) gamma-ray beam by laser Compton scattering of the 1.94-μm fiber laser.

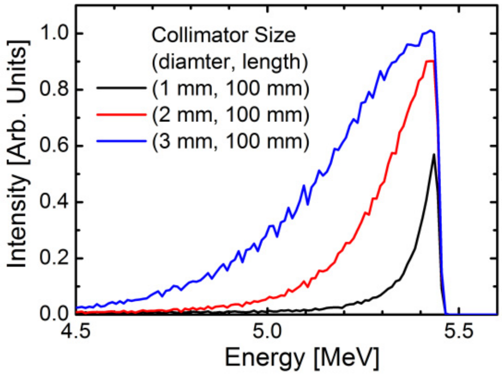

Fig.5. Expected Gamma-ray Spectra with Different Hole Size of Collimators Placed 8.5-m Downstream from Center of Straight Section

Table 3. The Expected Gamma-ray Flux and Energy Spread behind Collimator

Hole Size of Collimator [mm]	Flux after Collimator [ph/s]	Energy Spread [%]*
w/o collimator	1.7×10^{7}	-
3	1.4×10^{6}	5.4
2	6.8×10^{5}	2.9
1	1.5×10^{5}	1.1

*Calculated in Full Width at Half Maximum (FWHM).

5. EXPERIMENTAL RESULT

5.1. Maximum Energy of Scattered Gamma-ray

The maximum energy of scattered gamma-rays was measured to investigate the energy of the electron beam circulating in the UVSOR-III storage ring. The electron beam current and laser power in this experiment was 0.6 mA and 1.2 W, respectively. The energy spectrum measured by the HPGe detector was shown in Fig. 6. The energy calibration of the HPGe detector was performed with gamma-ray from ^{40}K (1460.8 keV) and ^{208}Tl (2614.5 keV). The high energy edge of the measured spectrum was fitted with error function, $f_{\mathrm{fit}}(E) = c_1\times\mathrm{erfc}\{(E - E_{\mathrm{max},0})/c_2\}+c_3$ [16]. Here we consider a_4 of equation 8 in reference [16] is equal to zero because of almost constant counts before the edge. As the result of fitting, the maximum gamma-ray energy $E_{\mathrm{max},0}$, which would be obtained in case of zero-energy-spread electron beam and detector with infinite resolution, was determined as 5403 ± 16 keV. Here we take systematic error of 0.3%, which can be caused by non-linearity of ADC or error of energy calibration, because we had no calibration source around 5.4 MeV in the experiment. From this result, the mean electron beam energy is estimated as 746 ± 1 MeV.

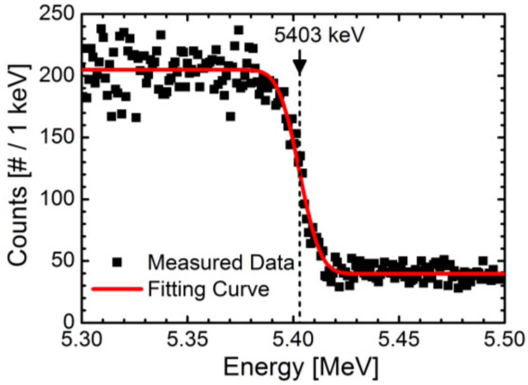

Fig.6. Measured Result of Maximum Energy of Scattered Gamma-ray

5.2. Total Flux Measurement under Low Flux Condition

The total flux was measured under low electron beam current (0.4 mA) and low laser power (1.2 W) condition. A HPGe detector was used in this experiment and gamma-ray events were accumulated for 600 s. The result of the measurement is plotted in Fig. 7 together with a numerical simulation result obtained by using EGS5 where 1×10^7 gamma-rays were randomely generated between the two bending magnets with keeping the relationship between the scattering angle and the gamma-ray energy defined by equation 1. In the numerical simulation, the geometry of the experiment and the responce function of the HPGe detector are taken in to account.

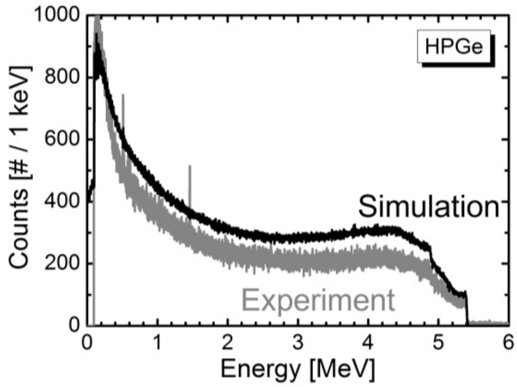

Fig.7. Measured Gamma-ray Spectrum and Spectrum Given by Numerical Simulation Using EGS5

As shown in Fig. 7, the shape of the measured spectrum can be reproduced by the numerical simulation. The vertical axis of the simulation result is normalized to have a number of generated gamma-rays to be 3.17×10^6, which given by multiplying 0.4×10^{-3} A, 1.2 W, 1.1×10^7 photons $s^{-1}A^{-1}W^{-1}$ and 600 s. In order to have a good agreement between the experiment and simulation results, we need to multiply 0.7 to the simulation. The total generated gamma-ray could be lower due to non-uniform electron and laser beam size in the collision region. From this experiment, we can estimate the maximum gamma-ray flux as around 1.2×10^7 photons/s in the case of beam current of 300 mA and laser power of 5 W.

5.3. Total Flux Measurement under High Flux Condition

Total flux of generated gamma-rays has been measured by using a $LaBr_3$(Ce) detector under the high beam current (300 mA) and high laser power (5 W) condition. Since the total gamma-ray flux in this condition can be higher than 1.0×10^6 photons/s and the detector strongly suffered from pileup of events, a lead absorber of 15-cm thickness was put in the upstream of the detector to reduce the incoming flux of the gamma-ray. The reduction ratio of 2-5MeV gamma-ray beam is calculated to be 7×10^{-4}.

The measured spectrum is plotted in Fig. 8 together with results of numerical calculations done by EGS5 which takes into account the lead absorber. In case of the calcualtion with the total gamma-ray flux of 7.0×10^6 photons/s, the simulation result shows a good agreement with the measured data in the energy range from 4.8 to 5.4 MeV. However, in the energy range from 2 to 4.8 MeV, the simulation result with the total gamma-ray flux of 1.1×10^7 photons/s shows a good agreement with the measured data. The discrepancy of the measured spectrum and the simulation results is possibly caused by a simplified geometry used in the simulation. From these results, the total gamma-ray flux generated by LCS between the electron beam in UVSOR-III and the 1.94-μm fiber laser can be estimated as $(0.7–1.1)\times10^7$ photons/s. This estimated flux is not so much different from a flux estimated from low current and low power experiment, 1.2×10^7 photons/s.

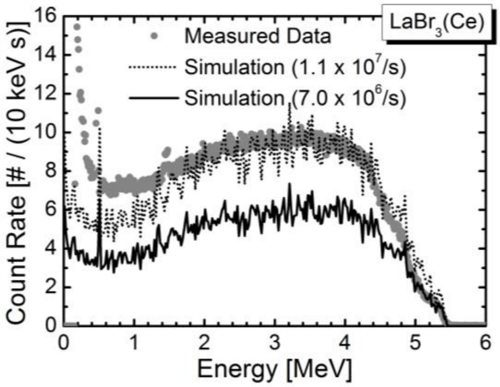

Fig.8. Measured Energy Spectrum of Gamma-ray Beam with a Lead Absorber whose thickness was 15 cm and Simulation Results with Two Different Total Gamma-ray Fluxes, 1.1×10^7 (Dotted Line) and 7×10^6 photons/s (Solid Line)

From low and high flux measurements, we can conclude that the total flux of LCS gamma-ray available with the present setup is around 1×10^7 photons/s. The gamma-ray flux behind a collimator with a 2-mm hole is around 4% of the total gamma-ray flux from numerical calculation results shown in the Table 3. Therefore, we can expect the gamma-ray flux of about 4×10^5 photons/s with energy bandwidth of 2.9% in FWHM. Those values are superior to the gamma-ray beam properties obtained in a storage ring TERAS, gamma-ray flux of around 10^5 photons/s with energy bandwidth of 7% in FWHM [10]. Therefore we can conclude that the quality of generated gamma-ray beam is enough to perform basic study on the non-destructive three dimensional isotope imaging.

6. CONCLUSION

Development of a laser Compton scattering gamma-ray source using a 1.94-μm fiber laser is undergoing in the UVSOR-III storage ring. As the first step of the development, basic characteristics of the gamma-ray source have been measured. The maximum gamma-ray energy was determined as 5403 ± 16 keV and the electron beam energy was evaluated to be 746 ± 1 MeV. Two measurements were conducted to determine the total gamma-ray flux can be generated with the present setup. One measurement was the direct measurement under the condition with low electron beam current (0.4 mA) and low laser power (1.2 W). The other is the measurement with a lead absorber with a thickness of 15 cm under the condition of the highest beam current (300 mA) and highest laser power (5 W). The total flux was estimated to be around 1.2×10^7 and $(0.7\text{-}1.1)\times10^7$ photons/s from the direct measurement and the measurement with absorber, respectively. The total flux expected from a numerical calculation was about 1.7×10^7 with an assumption of constant electron beam size and laser beam size along the interaction region. The estimated fluxes were not so much different from the expected flux and we can conclude that the total flux available in the current system is around 1×10^7 photons/s. From those experimental results and numerical calculations, generation of a quasi-monochromatic gamma-ray beam with the flux of about 4×10^5 photons/s and the energy bandwidth of 2.9% in FWHM can be expected to be available by putting a collimator with a 2-mm hole. This high quality gamma-ray can be used for our target application, the basic research of non-destructive three dimensional isotope imaging.

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