ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-THPOMS046

GENERATION OF FLAT-LASER COMPTON SCATTERING GAMMA-RAY BEAM IN UVSOR

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Abstract

Flat-Laser Compton Scattering Gamma-ray beam (F-LCS), which has a flat distribution in the energy spectrum and the spatial distribution with a small beam size, has been developed to study an isotope selective CT Imaging application in the beamline BL1U in UVSOR. We propose generation of an F-LCS beam by using a circular motioned electron beam, which can be generated by a helical undulator installed in a storage ring, and collision with an intense laser beam. A simulation study on the LCS beamline BL1U in UVSOR shows a weak magnetic field (K=0.2) can generate an F-LCS beam. A demonstration experiment has been carried out in UVSOR with the APPLE-II undulator. The spectra of the LCS beams were measured by using a 120% Ge detector. As a result, the energy bandwidth of the LCS peak was observed. The energy bandwidth measured in the energy spectra and the distribution map agreed with the EGS5 simulation.

INTRODUCTION

Flat-Laser Compton Scattering Gamma-ray beam (F-LCS), which has a flat distribution in the energy spectrum and the spatial distribution, has been developed to study an isotope selective CT Imaging application. We have successfully demonstrated a three-dimensional (3D) isotope-selective CT image of an enriched ^{208}Pb sample inserted into an aluminium cylindrical holder with isotope enriched ^{206}Pb by using a conventional LCS beam to excite Nuclear Resonance Fluorescence (NRF) [1]. However, for obtaining a good image resolution in CT, the small beam size of the incident LCS beam is required, which makes it challenging to excite different isotopes at the same time because of the narrow energy bandwidth of the LCS beam. In addition, the energy spectrum of the LCS beam has a scattering angle dependence which makes that the energy spectrum of the LCS beam has a spatial dependency. Therefore, we have proposed the F-LCS beam which has broader energy bandwidth with a small beam size and a spatially uniform energy spectrum, which can be generated by using a helical undulator such as the APPLE-II undulator installed at the BL1U beamline in the UVSOR synchrotron facility [2] to excite a circular motion of the electron beam circulating in the storage ring. In this paper, we briefly explain the concept of generation of an F-LCS beam, EGS5 [3] simulation result, and the demonstration experiments carried out in 2021 and 2022.

PRINCIPLE OF F-LCS BEAM GENERATION

LCS beams are generated by the collision between a relativistic electron beam and an intense laser beam [4]. The backscattering laser photon, whose energy is E_p, has a scattered angle (θ_γ) - energy dependency as described in the following formula [4],

$$E_\gamma = \frac{E_p\left(1+\beta\cos\theta_p\right)}{1-\beta\cos\theta_\gamma+\frac{E_p}{E_e}\left(1-\cos\theta_s\right)},$$

where E_γ is the energy of the backscattered laser photon, E_e is the electron energy, β is the electron velocity relative to the speed of light, θ_p is the incident laser angle, and θ_s is the angle between the incident laser photon and the scattered photon.

By using a small collimator to define the scattering angle, we can generate a narrow bandwidth LCS beam described as

$$\frac{\sigma_{E_\gamma}}{E_\gamma} = \sqrt{\left(\frac{\sigma_\theta}{E_\theta}\right)^2+\left(\frac{\sigma_\gamma}{E_\gamma}\right)^2+\left(\frac{\sigma_L}{E_L}\right)^2+\left(\frac{\sigma_\varepsilon}{E_\varepsilon}\right)^2},$$

where the terms in the right-hand side correspond the contribution to the bandwidth of the LCS beam from the collimator, the electron energy spread, the laser bandwidth, and the electron beam emittance, respectively [5].

To reduce the angle dependence, it is obvious to use a large energy spread and/or a large emittance electron beam. However, in general, LCS facilities use an electron beam circulating in a storage ring whose energy spread is small ($<10^{-3}$) with low unnormalized emittance (<1 μmrad).

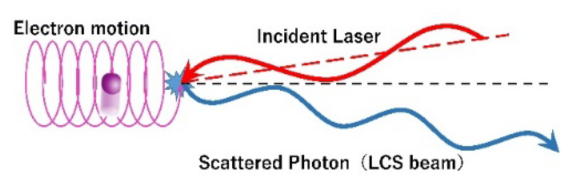

Figure1: Conceptual drawing of F-LCS beam generation.

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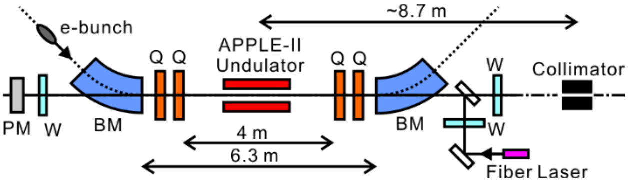

Figure 2: Schematic drawing of the BL1U beamline in UVSOR. Optical Klystron type undulator containing twin helical undulators of APPLE-II type and a buncher magnet are installed in 4.3 m free space. PM: power meter, W: window, SM: Spherical Mirror.

We propose to use a helical undulator, which is available in many synchrotron radiation facilities to excite a circular motion of the electron beam at the collision region of LCS generation. Figure 1 shows a conceptual drawing of F-LCS beam generation. It is obvious that the circular motion electron beam has a large divergence angle that works to broaden the energy spread of the LCS beam. In the following sub-section, we describe our simulation study to confirm the generation of the F-LCS beam by using a circular moving electron beam.

EGS5 Simulation

We performed a simulation developed in UVSOR using the EGS5 code. The BL1U beamline in UVSOR (Fig. 2) was assumed to be used for the test experiment where the Apple-II undulator (period of 8.8 cm) was installed at the center of the 6.3-m straight section. The circular electron beam collides with an incident laser uniformly at the undulator section with a 1.76-m long.

Figure 3 (a) shows the LCS gamma-ray energy distribution along the vertical axis (y) after passing through a 2 mm collimator with the undulator K-value of 0. A position–energy dependency is clearly indicated. When the undulator turns on K=0.2, the position-energy dependency is relaxed as shown in Fig. 3 (b). Because the wiggling motion with K=0.2 is calculated to be the electron beam circular radius of about 15 μm, which is comparable to the electron beam size (20 μm) in the vertical axis, the excited beam divergences are considered to be the main reason for the generation of the F-LCS beam.

The energy spectra of the LCS beams with different K-values from 0 to 0.5 were calculated, and the results are shown in Fig. 4. The wider energy bandwidth is generated with a larger K-value. The energy bandwidth is widened from 2.5 to 20.3% (FWHM) and the peak energy is shifted from 5.52 MeV to 4.64 MeV according to the increment of the K-value=0 to 0.5. Although the energy spectrum is not completely flat, about eight times the large bandwidth can be obtained with the same collimator of 2 mm ϕ. It should be noted that the yield of the LCS beam decreases with the increase of the undulator field. Therefore, as a candidate for the F-LCS generation in UVSOR, we choose K=0.2 whose energy bandwidth and peak energy are 7.2% (FWHM) and 5.50 MeV, respectively.

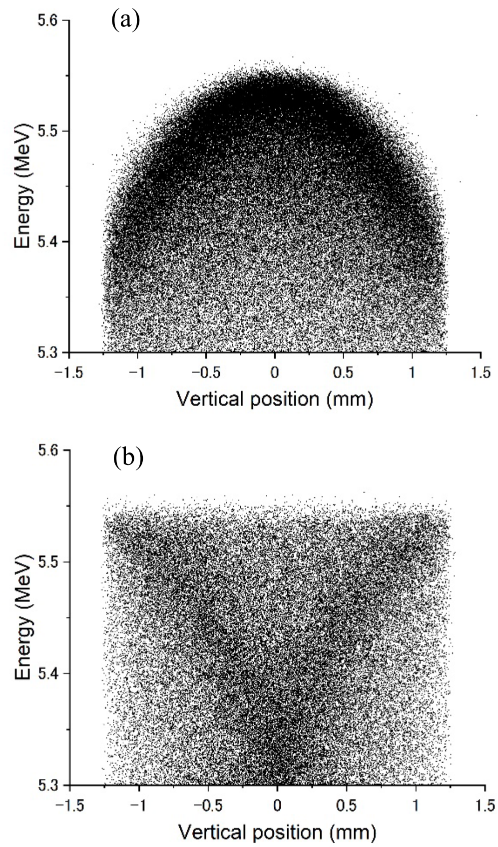

Figure 3: LCS gamma-ray energy distribution in the vertical axis with the undulator K-value of (a) K=0 and (b) K=0.2.

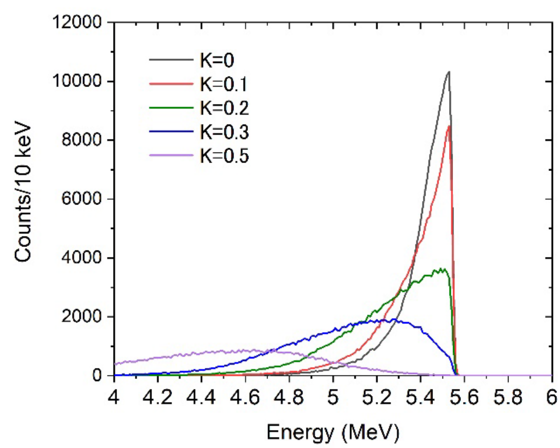

Figure 4: Energy spectra of the gamma-ray beams with different K-values from 0 to 0.5.

EXPERIMENT AT BL1U IN UVSOR

The F-LCS beam generation was examined at BL1U in UVSOR. The experimental setup is displayed in Fig. 2. The stored electron beam with an energy of 746 MeV with a current of around 6 mA was used. LCS beams with a maximum energy of 5.528 MeV were generated by a head-on collision between the electron beam and a laser beam from a Tm-fiber system (TLR-50-AC-Y14, IPG Laser GmbH) with around 1 W CW power with random polarization. The laser wavelength was 1.896 μmand the

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spectral linewidth was 0.7 nm. A 2-mm diameter collimator of 20 cm × 10 cm × 10 cm lead block was placed after passing through the vacuum window. A high-purity germanium (Ge) detector with an efficiency of 120% relative to a 3” × 3” NaI(Tl) scintillator measured the energy spectra of the gamma-ray beams.

Before the LCS gamma-ray generation, we examined the electron beam orbit distortion by excitation of the undulator to confirm that the undulator field does not affect the other beamline users. The beam position monitor located in BL1U showed the orbit change by the undulator field of K=0.2 was about 25 µm on the horizontal axis and 50 µm on the vertical axis, which are acceptable changes for the other beamline users.

Figure 5 shows the measured gamma-ray beam spectra with the undulator K-value of 0, 0.1, 0.2, and 0.3. Although the Ge could not fully stop the gamma-rays whose energies were around 5 MeV, the clear LCS peak at 5.5 MeV with K=0 gradually disappeared by increasing the undulator K-value. The tendency of the peak bandwidth broadening agrees with the EGS5 simulation.

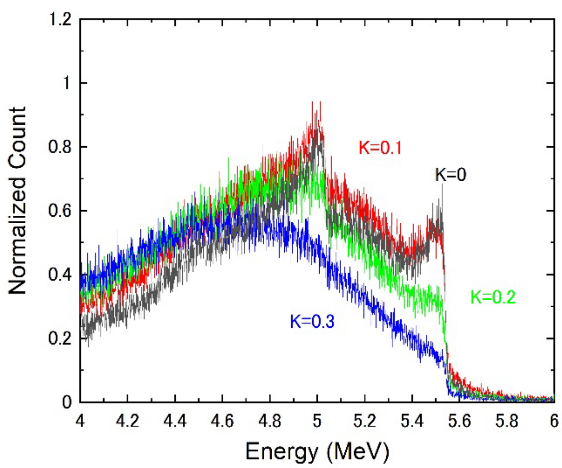

Figure 5: Measured LCS beam spectra with the undulator K-value of 0, 0.1, 0.2, and 0.3. The LCS beam was collimated with 2 mmϕ lead collimator.

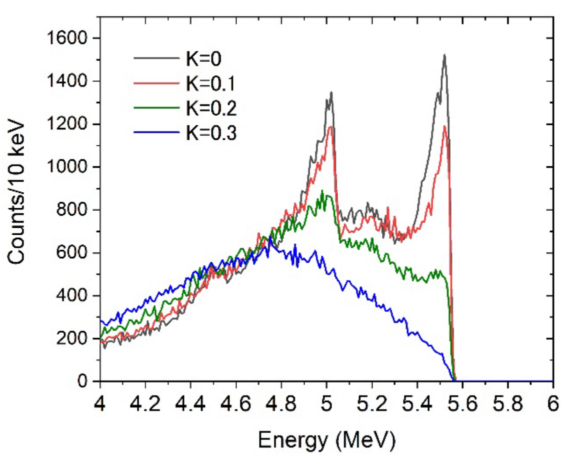

Figure 6: LCS energy spectra calculated EGS5 including Ge detector response.

DISCUSSION AND CONCLUSION

To compare the spectra from the simulation and the experiment, EGS5 calculation including the Ge detector response was performed. Figure 6 shows the result of the simulation. The experimental broadening of the energy bandwidth was slightly larger than the simulation result, but the LCS spectra calculated with EGS5 well reproduce these from the experiment. This slight difference may come from our simple model of the circulating electron beam. In addition, although the Apple-II undulator installed in the BL1U which is an Optical Klystron type has a dispersive section, our model omitted this section.

In this paper, we have proposed a generation of F-LCS beams with a broad energy bandwidth and a small beam size using a helical undulator in a storage ring. A simulation calculation using EGS5 shows the energy bandwidth of the LCS beam with circular motion excited by a helical undulator is widened from 2.5 to 20.3% (FWHM) with fixed collimator size (2 mm ϕ) from K=0 to K=0.5 in the BL01 in UVSOR. The F-LCS beam generation has been carried out at the BL1U in UVSOR. The APPLE-II undulator was used to generate the circular motion of the electron beam. The energy spectra have been measured with a 120% Ge detector with K=0, 0.1, 0.2, 0.3, and the results agree with the EGS5 simulation. This result supports the successful generation of the F-LCS beam. The spatial distribution of the F-LCS beam and precise modeling of EGS5 simulation should be performed in further study.

ACKNOWLEDGEMENTS

This work was supported by the Japanese Sociality for the Promotion of Science (JSPS) KAKENHI under Grants 21H01859 and performed at the BL1U of UVSOR Synchrotron Radiation Facility with the approval of Institute for Molecular Science (IMS), National Institute of Natural Science (NINS) (Proposal No. 21-603, 21-806).

REFERENCES

[1] K. Ali *et al.,* “Three-dimensional nondestructive isotope-selective tomographic imaging of 208Pb distribution via nuclear resonance fluorescence”. *Appl. Sci.* vol. 11, p. 3415, 2021.

[2] M. Adachi, H. Zen, T. Konomi, J. Yamazaki, K. Hayashi and M. Katoh, “Design and construction of UVSOR-III”, *J. Phys. Conf. Ser.,* vol. 45, p. 042013, 2013.

[3] H. Hirayama, Y. Namito, A.F. Bielajew, S.J. Wilderman and W.R. Nelson, “The EGS5 code system”, SLAC Report number: SLAC-R-730 and KEK Report number: 2005-8.

[4] F.R. Arutyunian and V.A Tumanian, “The Compton effect on relativistic electrons and the possibility of obtaining high energy beams”, *Phys. Lett*., vol. 4, pp.176-178, 1963.

[5] R. Hajima, “Bandwidth of a Compton radiation source with an electron beam of asymmetric emittance”, *Nucl. Inst. and Methods in Phys. Res., A,* vol. 985, p.164655, 2021.