# GENERATION OF ULTRA-SHORT GAMMA-RAY PULSES BY LASER COMPTON SCATTERING IN AN ELECTRON STORAGE RING

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*Abstract*

We are developing an ultra-short pulse gamma ray source with pulse width of sub-picosecond by laser Compton scattering technology. We have proposed to generate the ultra-short gamma ray pulses by injecting femtosecond laser pulses into the electron beam circulating in an electron storage ring from the vertical direction. The head-on and horizontal 90° collision experiments were carried out at the electron storage ring UVSOR-II. The measured energy and intensity of the gamma rays agreed well with the theoretical estimation.

## INTRODUCTION

Scattering of laser photons by relativistic electrons results in laser Compton scattered (LCS) gamma rays [1]. The LCS gamma rays have excellent characteristics of large intensity, quasi-monochromaticity, tunable in energy, narrow in angular spread, and high polarization. They are useful for applications such as nuclear physics [2], polarized positron generation [3], nondestructive inspection [4], and electron beam diagnosis [5].

The pulse width of the LCS gamma rays can be in the sub-picosecond range by using a femtosecond pulse laser. However, even for long electron bunches, the interaction time between an electron beam and a laser can be shortened by injecting a laser from the vertical direction into an electron beam because the size of an electron beam is a few tens of millimeters in the longitudinal direction, a few hundreds of microns in the horizontal direction, and a few tens of microns in the vertical direction. It is expected that this ultra-short pulse gamma rays and ultra-short pulse positrons generated from the gamma rays will be applicable to measure ultra-fast phenomena.

A similar technique was used for generating ultra-short pulse X-rays by using a low-energy electron beam in a linac [6]. This technique is more effective when it is applied to the electron beam circulating in an storage ring. This is because the beam size in the vertical direction is very small. However, there is no report that this technique was applied for generating ultra-short gamma ray pulses at an electron storage ring.

In this paper, we will present the estimation of the energy, intensity, and pulse width of the LCS gamma rays, and results of the head-on [7] and horizontal 90° collision experiments at the electron storage ring UVSOR-II. The purpose of these experiments is to confirm the generation of the LCS gamma rays by comparing the gamma ray spectrum with the calculated one in the head-on collision and to establish the method for the timing adjustment between the electron beam and the laser in the horizontal 90° collision.

## ESTIMATION FOR VERTICAL 90° COLLISION

According to the relativistic kinematics between the laser photons of energy $E_{\rm L}$ and the electron beam, the scattered photons have energy [8] of

$$E_\gamma = \frac{E_{\rm L}(\beta\cos\alpha + 1)}{1-\beta\cos\theta + \frac{E_{\rm L}}{\gamma m_{\rm e}c^2}\{1+\cos(\alpha+\theta)\}}. \quad (1)$$

Here, $\theta$ is the angle between the scattered photon and the electron beam, $\alpha$ the collision angle between the laser and the electron beam ($\alpha$ = 0 for a head-on collision), $\gamma$ the Lorenz factor, $m_{\rm e}c^2$ (= 0.511 MeV) the electron energy at rest, and $\beta = v/c$ ($v$ is the electron velocity and $c$ the light velocity).

The number of gamma rays per unit time $N_\gamma$ is expressed as the product of a scattering cross section and the luminosity $L$ [9]. If electron beam energy is lower than GeV region, the cross section is almost equal to Thomson scattering cross section $\sigma_{\rm T}$.Thus the intensity is

$$N_\gamma = L\sigma_{\rm T}. \quad (2)$$

A half of the gamma rays are scattered into a very narrow cone $\theta < 1/\gamma$ into the forward direction of the electron beam. On the other hand, the luminosity $L$ for the vertical 90° collision is given by [9]

$$L = \frac{fN_{\rm e}N_{\rm p}\cos(\alpha/2)}{2\pi\sqrt{\sigma_{\rm X}^2}\sqrt{\sigma_{\rm Y}^2\cos^2(\alpha/2)+\sigma_{\rm Z}^2\sin^2(\alpha/2)}}. \quad (3)$$

Here, $\sigma_{\rm X}^2 = \sigma_{x{\rm e}}^2 + \sigma_{x{\rm p}}^2$, $\sigma_{\rm Y}^2 = \sigma_{y{\rm e}}^2 + \sigma_{y{\rm p}}^2$, $\sigma_{\rm Z}^2 = \sigma_{z{\rm e}}^2 + \sigma_{z{\rm p}}^2$, $f$ is the collision frequency, $N_{\rm e}$ the number of electrons, $N_{\rm p}$ the number of laser photons, and $\sigma_x, \sigma_y$, and $\sigma_z$ the rms horizontal, vertical, and longitudinal beam size, respectively. Subscripts e and p indicate the electron and laser, respectively.

The pulse width $\sigma_{\rm t}$ of the gamma rays in the case of the 90° collision is [10]

$$\sigma_{\rm t} = \frac{\sigma_{z{\rm e}}\sqrt{\sigma_{z{\rm p}}^2+\sigma_{y{\rm e}}^2+\sigma_{y{\rm p}}^2}}{c\sqrt{\sigma_{z{\rm e}}^2+\sigma_{z{\rm p}}^2+\sigma_{y{\rm e}}^2+\sigma_{y{\rm p}}^2}} \quad (4)$$

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To generate the ultra-short gamma ray pulses, the size of the laser should be the same as that of the electron beam.

The pulse width, intensity, and energy of the LCS gamma rays were estimated by using the theoretical equations (1) to (4) for the case of UVSOR-II with a femtosecond Ti:Sa laser. The parameters of the electron beam were set as follows; energy, 750 MeV; revolution frequency, 5.64 MHz; stored beam current, 100 mA; horizontal and vertical beam size (rms), 0.60, 0.03 mm; and pulse width (rms), 108 ps. The parameters of the laser were set as follows; wavelength, 800 nm; repetition frequency, 1 kHz; pulse energy, 10 mJ; beam size, 0.03 mm; and pulse width (FWHM), 130 fs. Estimated parameters of the gamma rays in vertical 90° collision were as follows; pulse width (rms), 150 fs; intensity, $2.4\times10^6$ photons $s^{-1}$; and maximum energy, 6.6 MeV. In these conditions, energy loss of the electrons through the collision does not exceed the RF bucket height. Therefore the generation of the gamma rays is able to coexist with the operation for the synchrotron radiation users.

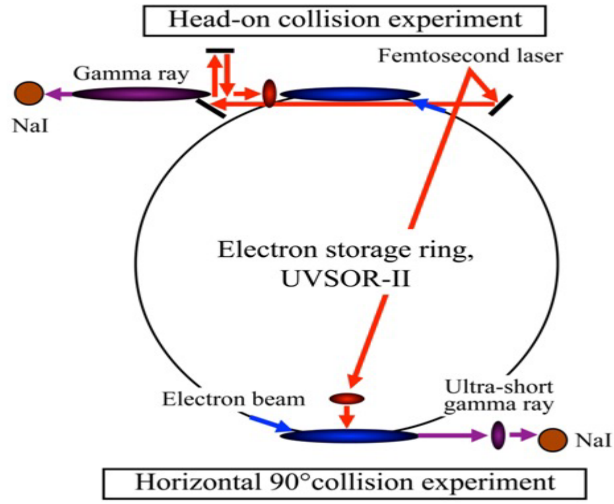


Figure 1: A schematic illustration of the head-on and horizontal 90° collision experiments.

## EXPERIMENTS

A schematic illustration of the experiments is shown in Fig. 1. UVSOR-II [11] is a third generation synchrotron light source. It consists of a 15 MeV linear accelerator, a 750 MeV booster synchrotron, and a 750 MeV storage ring. The storage ring has a structure of a four fold symmetry, has eight straight sections and eight bending magnets, and its circumference is 53.2 m. The storage ring is normally operated with the beam current 350 mA (multi bunch) and its natural emittance is 27.4 nm-rad.

The collision points were at the straight sections of the storage ring. An optical port for the free electron laser was used for the injection of the laser in the head-on collision experiment and a vacuum chamber for the beam diagnostics was used in the horizontal 90° collision experiment. The electron beam was operated in the beam current around 1 mA (single bunch), much lower than the normal operating condition, to avoid pile-up in the detector.

The laser pulse was provided by a Ti:Sa laser system (COHERENT, LEGEND-HE) synchronized with an RF frequency of the storage ring, 90.1 MHz. The wavelength and the frequency of the laser were 800 nm and 1 kHz respectively. Since the laser system was 20 m away from the collision point in the horizontal 90° collision experiment, the laser was sent to the collision point in air by multilayer mirrors. The laser power at the collision points was calculated 0.25 W in the head-on collision and 1.5 W in the horizontal 90° collision from the attenuation at the mirror and windows. Lenses were not set up on the axis of the laser beam. The size of the laser was few mm in the head-on and horizontal 90° collision experiments.

The gamma rays were detected by a NaI scintillator (1600 $cm^3$) and the absorption energy was measured. NaI scintillator was set 7.6 and 6.5 m apart from the collision point in the head-on and horizontal 90° collision experiments. The detector system consists of the NaI scintillator with electronics, a shaper amplifer, and a multichannel analyzer. A gate signal synchronized with the laser injection was sent to the multichannel analyzer. The noises from bremsstrahlung gamma rays were reduced. For energy calibration of the detector, $^{137}$Cs and $^{60}$Co were used and calibration coefficients were decided by a least squares fit. For the head-on collision experiment, a collimator was placed in front of the detector to restrict the angular acceptance. The collimator was a lead block 10 cm thick with a hole 5 mm in diameter.

For the timing adjustment between the electron beam and the laser, a pick-up electrode near the collision point and a photodiode were used. The timing of the laser was adjusted so that the time difference of two waveforms on an oscilloscope became the same the distance between a pick-up electrode and the collision point.

## RESULTS AND DISCUSSION

The experimental data of the energy spectra were shown in Fig.2. We have succeeded in detecting the LCS gamma rays in both the head-on and horizontal 90° collisions. These spectra were compared with the numerical calculation of the response of the detector by the EGS5 code [12].

EGS5 is a Monte Carlo simulation code for the transport of elecrons and photons with energies ranging from keV to PeV. The energy and intensity of the LCS gamma rays are defined by Eqs. (1) to (3) in the EGS5 code. In the calculation, the lead collimator was included for the head-on collision. The effect of the emittance and energy spread of the electron beam were disregarded.

The numerical results were shown in Fig. 2. In the head-on and horizontal 90° collision without the collimator, the measured spectra agreed well with the calculated spectra. In the head-on collision with the collimator, the measured

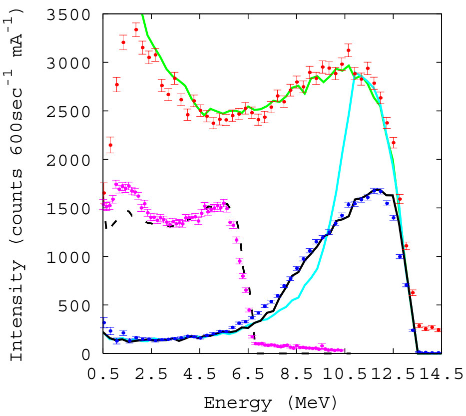


Figure 2: The energy spectra of measurement and calculation in head-on and horizontal 90° collision. The experimental data shows as follows; red points, head-on collision without collimator; blue points, head-on collision with collimator; pink points, horizontal 90° collision. The numerical calculation shows as follows; green curve, head-on collision without collimator; light blue curve, head-on collision with collimator; black curve, head-on collision with collimator shifted by 1.7 mm; dashed black curve, horizontal 90° collision. The measurement time was 600 seconds respectively. The intnesity was standardized by the beam current values. The background was subtracted mainly due to the bremsstrahlung gamma rays. The measurement data of every 100 channels was added. The error of a vertical is stastic error.

spectrum agreed well with the calculated spectrum under an assumption that the collimator is shifted by 1.7 mm horizontally from the center axis of the gamma rays by misalignment. The disagreement between the measured spectra and the calculated spectra at low energy region is due to the shortage of the information on the materials in the calculation. A complicated structure of a beamline was not inputted in the calculation, and the spectrum in the low energy region was influenced by backscattered and absorbed gamma rays. In the measurement without the collimator, gamma rays were detected with energies higher than the maximum energy of 6.6 or 13.1 MeV due to the pile-up in the detector.

Although, the pulse width is not able to be experimentally measured at present, it was calculated to be 5 ps under the experimental conditions in the horizontal 90° collision by Eq. (4)

## CONCLUSION

We plan to generate the ultra-short pulse gamma rays with pulse width of sub-picosecond width via laser Compton scattering in the electron storage ring.

We carried out the head-on and horizontal 90° collision experiments. The experimental data was compared with a simulation calculated by the EGS5 code. The energy and intensity of the gamma rays were consistent with the calculations.

Recently, we have carried out a vertical collision experiment using the same vacuum chamber of the horizontal 90° collision experiment and succeeded in generating the gamma rays of tunable energy[13]. We will challenge the measurement and application of the ultra-short pulse gamma rays.

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