DEVELOPMENT OF PULSE WIDTH MEASUREMENT TECHNIQUES IN A PICOSECOND RANGE OF ULTRA-SHORT GAMMA RAY PULSES*

Y. Taira#, N. Yamamoto, M. Hosaka, K. Soda, Nagoya University, Nagoya, Japan
M. Adachi, H. Zen**, T. Tanikawa##, M. Katoh, UVSOR, Okazaki, Japan

Abstract

Ultra-short gamma ray pulses of the picosecond and femtosecond range can be generated using laser Compton scattering with 90-degree collisions at the UVSOR-II electron storage ring. Measurement techniques for a gamma ray pulse width in the sub-picosecond to picosecond range are being developed. As the first stage of the development, we tested a pulse width measuring method for the gamma ray pulses with pulse width of 4.8 ps (FWHM) consisted of a multi-pixel photon counter (MPPC) and a digital oscilloscope. The time resolution of the MPPC was measured as 477 ps (FWHM) by using a single photon counting technique. It was indicated the shortest pulse width that the MPPC could evaluate was 82 ps under ideal conditions. However, the measured gamma ray pulse width was 540 ps. The main reason for the large discrepancy is considered to be the noise of the trigger signal synchronized with the gamma rays. The measured gamma ray pulse width can be lowered by increasing the signal-to-noise ratio of the trigger signal and using a fast photodetector, a microchannel plate photomultiplier tube (MCP-PMT) with a time resolution of few tens of picoseconds. As the next stage, we will develop a pulse width measurement technique in the femtosecond range by using a pump-probe technique with a femtosecond laser and ultra-short gamma ray pulses.

INTRODUCTION

Compton scattering of laser photons by a relativistic electron beam results in backscattered gamma rays [1]. This technique is called laser Compton scattering (LCS). LCS gamma rays are tunable in energy, quasi-monochromatic, highly polarized, and intense. Hajima et al. recently proposed a non-destructive assay system for radioactive nuclear wastes using LCS gamma rays [2]. In this case, the gamma rays are generated using an energy recovery linac as an ultra-short electron beam and a short-pulse laser; they are intense (10^{13} photons s^{-1}) and ultra-short pulses [pulse width, 11 ps (FWHM)]. Generation of ultra-short gamma ray pulses will be active with a development of an ultra-short electron beam. Thus, pulse width measurement techniques for ultra-short gamma ray pulses in the sub-picosecond to picosecond range will become important.

Ultra-short gamma rays can be generated by using an existing accelerator. An electron beam circulating in a storage ring is focused more tightly in the perpendicular direction than in the longitudinal direction. The pulse width (rms) of the gamma rays as a function of the collision angle between the electron beam and the laser is shown in Fig. 1. The ultra-short gamma ray pulses with sub-picosecond pulse width can be generated by injecting a laser from the vertical 90-degree direction into an electron beam [3]. The pulse width of the gamma rays generated in a vertical collision is shorter than that generated in a horizontal collision because the vertical beam size of the electron beam is smaller than its horizontal beam size. We are developing techniques to produce the ultra-short gamma ray pulses based on 90-degree collision and to measure the pulse width at the UVSOR-II electron storage ring [4].

We are investigating various possible techniques for pulse width measurement in the sub-picosecond to picosecond range. A pump-probe technique that uses a femtosecond laser and ultra-short gamma ray pulses is the most potential candidate. As the first stage of pulse width measurement, however, we examined a pulse width measurement technique in the picosecond range by using a multi-pixel photon counter (MPPC) consisting of multiple avalanche photodiode (APD) pixels operating in Geiger mode. In this paper, we report the results of a basic experiment.

ESTIMATION OF UPPER BOUND VALUE OF THE GAMMA RAY PULSE WIDTH

The gamma ray pulse width cannot be directly

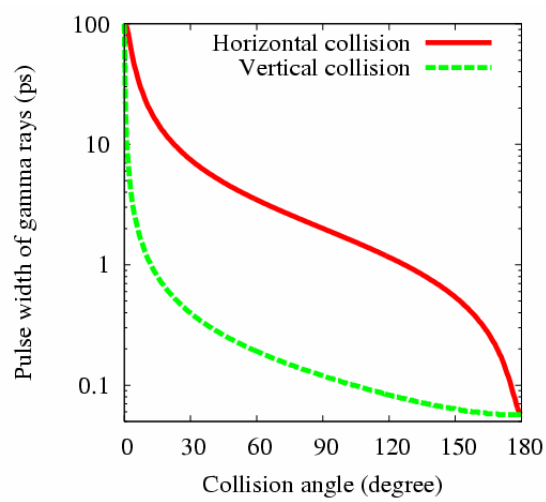

Figure 1: Dependence of the pulse width of the gamma rays on the collision angle. Solid line shows the horizontal collision which the laser is injected from the direction in the orbital plane. Dashed line shows the vertical collision which the laser is injected from the direction to the orbital plane.

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#tairayo@ims.ac.jp
**Present address is IAE, Kyoto University, Japan
##Present address is Lille University, France

evaluated in the femtosecond range by using an MPPC because its time resolution is sub-nanosecond. However, we can evaluate an upper bound value of the gamma ray pulse width in the picosecond range using an MPPC by applying the time resolution measuring method of a photodetector. This type of measurement generally examines the time between a start signal synchronized with a photon source and a stop signal output by the photodetector. The width of the measured timing distribution, T_{m}, is described as

$$T_{\mathrm{m}}^2 = T_{\mathrm{r}}^2 + T_{\mathrm{p}}^2 + T_{\mathrm{j}}^2 . \quad (1)$$

Here, T_{r} is the time resolution of the photodetector, T_{p} is the pulse width of the photon source, and T_{j} is the time jitter of the measurement system. The width of the measured timing distribution is almost equal to the time resolution of the photodetector in a measuring system in which the pulse width of the photon source and the time jitter are considerably smaller than the time resolution of the photodetector. The time resolution of the MPPC module (Hamamatsu Photonics K. K., C10507-11-100U) was measured using a short-pulse Ti:Sa laser and a single photon counting technique. The time resolution of the MPPC module was measured as 477 ± 7 ps (FWHM) by using Gaussian fitting.

We estimated the upper bound value of the gamma ray pulse width by using the MPPC module. The relationship between the width of the measured timing distribution and the pulse width of the gamma rays under ideal conditions (negligible time jitter) is shown in Fig. 2. If the pulse width of the gamma rays is larger than 82 ps, the measured timing distribution is larger than the time resolution of the MPPC module. Thus, the shortest pulse width that the MPPC can evaluate is 82 ps. Moreover, the upper bound value of the gamma ray pulse width can be lowered by improving the measurement precision of the time resolution or using a fast photodetector, a microchannel plate photomultiplier tube (MCP-PMT) with a time resolution of few tens of picoseconds.

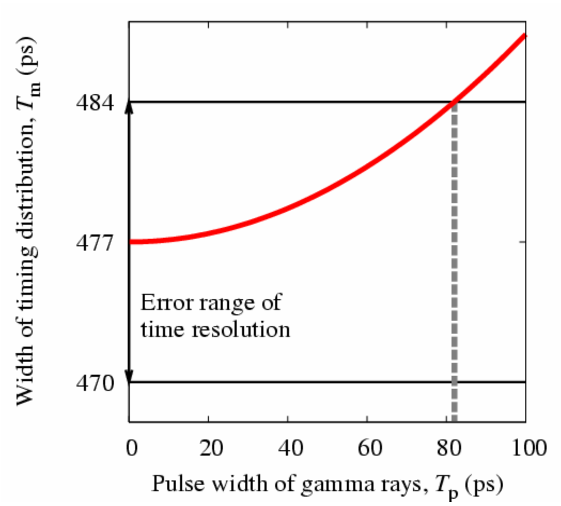

Figure 2: Relationship between the width of the timing distribution measured by the MPPC module and the pulse width of gamma rays for negligible time jitter (thick solid curve). Thin solid line shows the error range of the time resolution. Dashed line shows the shortest pulse width that the MPPC can evaluate.

EXPERIMENT

We carried out an experiment that evaluated the upper bound value of the pulse width of LCS gamma rays at UVSOR-II. A schematic representation of the experiment is shown in Fig. 3. The electron beam and the laser collided in a vacuum chamber along the straight section. The storage ring was operated with a beam energy of 750 MeV and a beam current of 15 mA (single bunch), which is lower than the normal operating conditions. The horizontal and vertical beam sizes (rms) at the collision point were 0.60 and 0.03 mm, respectively. The pulse width of the electron bunch was 350 ps (FWHM) when the beam current was 15 mA.

Laser pulses having a power of 2.8 W were provided by a Ti:Sa laser system (Coherent, Legend-HE) synchronized with the RF frequency of the storage ring, 90.1 MHz. The wavelength, repetition rate, and pulse width of the laser were 800 nm, 1 kHz, and 730 fs (FWHM), respectively. The laser light was transmitted to the collision point through air by high-reflection mirrors because the laser system was located ~20 m from the collision point. The laser was injected into the electron beam from the horizontal 90-degree direction (the direction in the orbital plane) through a magnesium fluoride window. The spot-size of the laser was focused at the collision point through a convex lens having a focal length of 125 mm, and was estimated to be 0.01 mm or less. The laser power in front of the window was measured to be 2.7 W by a power meter and estimated to be 2.4 W at the collision point, considering the absorption of the window.

The timing between the electron beam and the laser pulses was adjusted by using a pick-up electrode and a photodiode near the collision point. The spatial alignment was adjusted by changing the position of the laser.

LCS gamma rays were scattered along the axis of the electron beam. The maximum energy, intensity at the

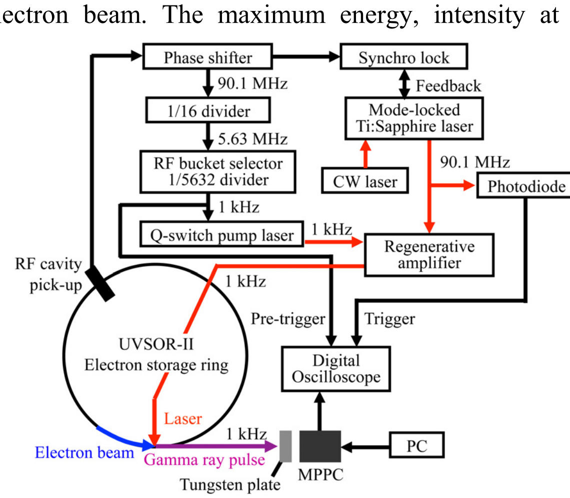

Figure 3: Schematic representation of the experiment.

collision point, and pulse width of the gamma rays were calculated as 6.6 MeV, 10^6 photons s^{-1}, and 4.8 ps (FWHM), respectively.

Since the MPPC cannot detect the gamma rays directly, Cherenkov radiation generated from the gamma rays was detected by the MPPC module. Cherenkov radiation was emitted in 0.35 mm thick UV glass attached to the MPPC when the charged particles (electrons and positrons) passed the UV glass. The charged particles were generated by irradiating a 0.5 mm thick tungsten plate with gamma rays. The positions of the tungsten plate and the MPPC module were determined by measuring the position of the gamma rays with an imaging plate beforehand. The distance between the collision point and the MPPC module was 5.5 m. The tungsten plate and the MPPC module were screened with a black curtain because the MPPC is highly sensitive sensors. The output signals from the MPPC module were measured by a digital oscilloscope (LeCroy, WaveRunner 104MXi), which has 4ch inputs, a sampling rate of 10GS/s, and a bandwidth of 1GHz. A divided signal from the RF cavity pick-up supplied a pre-trigger signal. A photodiode detecting the mode-locked laser supplied the trigger signal. The MPPC module outputs 100 mV with a rise time of 5 ns and a decay time of 150 ns on detecting a single photon. We measured the timing distribution of output signals from the MPPC module crossing a slice line at 50 mV by using the math function "phistogram" of the oscilloscope.

RESULT AND DISCUSSION

Figure 4 shows the experimentally obtained timing distribution between gamma rays and the trigger signal. The peak on the right is the distribution for single photon detection, and that on the left is the distribution of two photon detection. Because the MPPC module outputs 200 mV when it detects two photons, the timing of a two photon detection signal crossing a slice line (50 mV) is

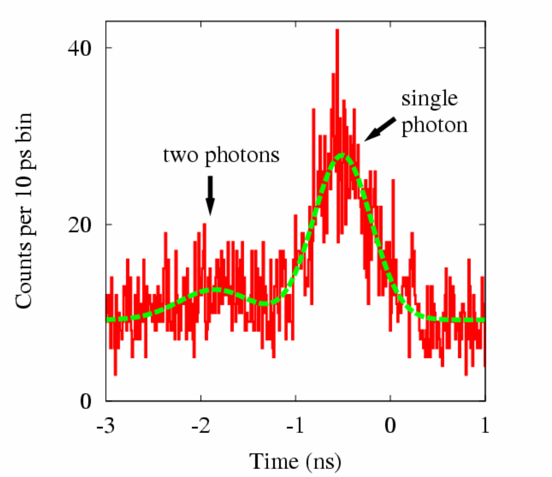

Figure 4: Experimentally obtained timing distribution between gamma rays and trigger signal. Dashed curve shows a result of Gaussian fitting. The width of the single-photon distribution is 720 ± 30 ps (FWHM).

earlier than that of a single photon detection signal. In this measurement, the timing distribution had a background of the MPPC's dark count; the dark count can be reduced by lowering the temperature. The width of the single photon distribution was found to be 720 ± 30 ps (FWHM) by using Gaussian fitting. The gamma ray pulse width including the time jitter was calculated as

$$\sqrt{T_{\mathrm{p}}^2 + T_{\mathrm{j}}^2} = 540 \pm 40 \text{ ps}$$

using Eq. (1). This value is considerably larger than the estimated upper bound value, 82 ps. This is most likely due to a large time jitter. The main reason for the large time jitter is considered to be the low signal-to-noise ratio of the trigger signal. The cable transmitting the trigger signal is ~30 m long. A time jitter of a few hundreds of picoseconds is easily generated by noise because the rise time of the trigger signal is 2 ns per 60 mV.

CONCLUSION

At the UVSOR-II electron storage ring, an ultra-short gamma ray pulse source has been developed using a laser Compton scattering technique. Pulse width measurement techniques for gamma rays in the femtosecond and picosecond ranges are being developed. A multi-pixel photon counter (MPPC) with picosecond time resolution was used for the pulse width measurement of the gamma ray pulses with pulse width of 4.8 ps (FWHM). It was indicated that the shortest pulse width the MPPC could evaluate was 82 ps under ideal conditions with negligible time jitter. However, the experimental data were affected by the time jitter. The measured gamma ray pulse width including time jitter was 540 ps. We will lower the upper bound value of the gamma ray pulse width by increasing the signal-to-noise ratio of the trigger signal and using a fast photodetector, a microchannel plate photomultiplier tube. Moreover, we will develop a pulse width measurement technique for ultra-short gamma rays in the femtosecond range by using a pump-probe technique.

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