FEMTO-SECOND PROFILE MONIITOR USING PULSED LASER STORAGE IN AN OPTICAL CAVITY*

K. Sakaue,† M. Washio, Waseda University, Tokyo, Japan
S. Araki, M. Fukuda, Y. Higashi, Y. Honda, T. Taniguchi, N. Terunuma,
J. Urakawa, KEK, Ibaraki, Japan
N. Sasao‡, Kyoto University, Kyoto, Japan

Abstract

We have been developing a pulsed-laser storage technique in a super-cavity for a compact x-ray sources. The pulsed-laser super-cavity enables to make high peak power and small waist laser at the collision point with the electron beam. Recently, using 357MHz mode-locked Nd:VAN laser pulses which stacked in a super-cavity scattered off a multi-bunch electron beam, we obtained a multi-pulse x-rays through the laser-Compton scattering. Detecting an x-ray pulse-by-pulse using high-speed detector makes it possible to measure the 3-dimensional beam size with bunch-by-bunch scanning the laserwire target position and pulse timing. This technique has a feasibility of measuring femto-second bunch length by stacking femto-second pulse in an optical cavity. Design study of femto-second laser-wire monitor and the experimental demonstration using pico-second pulse storage and multi-bunch electron beam will be presented at the conference.

INTRODUCTION

SASE FEL requires high peak current electron beam to obtain enough gain, thus the various SASE FEL project adopted a bunch compressor and compress the bunch length down to less than 100fsec. In order to measure ultra short bunch length and the longitudinal bunch profile, many different approaches were proposed and demonstrated, such as electro-optic technique[1] and transverse deflecting cavity[2].

We have been developing a laser storage technique in an optical cavity. At the beginning, a laserwire beam profile monitor was established as non-destructive beam profile monitor at KEK-ATF damping ring using cw laser storage. Laser storage in an optical cavity enhances the laser power and enables to make small waist laser stably at the center of the optical cavity. This monitor was successfully demonstrated to measure the extremely low emittance beam and multi-bunch electron emittance with bunch spacing of 2.8nsec produced in ATF damping ring[3]. We have been also developing a pulsed-laser storage technique for a compact X-ray source based on laser-Compton scattering. This compact X-ray source was firstly proposed by Huang and Ruth in 1997 for electron beam cooling[4]. In this proposal, electrons and photons are stored in storage ring and super-cavity, respectively, and therefore electrons and photons continuously interact and generate a high flux X-rays through the laser-Compton process. We proposed to apply the laserwire technique for pulsed-laser stacking to achieve the high peak power photon target. To use this super-cavity and an electron storage ring, the high peak power laser in super-cavity is scattered by the electron beam continuously, and generate a high quality and high flux X-rays up to 10^{14}photons/sec[5]. As the first step of this proposal, we are performing a proof-of-principle experiment of laser-Compton scattering using pulsed-laser super-cavity and multi-bunch electron beam. We call this linac based X-ray source, ”LUCX” (Laser Undulator Compact X-ray source).

We have already succeeded in detecting pulse-train X-ray produced by laser-Compton scattering. During the X-ray generation experiment at LUCX project, we found that this pulsed-laser storage cavity can be used not only for transverse beam profile monitor but also longitudinal profile measurement and bunch spacing monitoring. As the electron linac produces larger number of bunches, variation of bunch spacing have been found and affected to produce a high quality electron beam.

These experimental results were obtained by using pico-second laser pulse and pico-second electron bunch. Laser storage technique can be applied for femto-second pulses, so that this monitor has feasibility to measure femto-second electron bunch length and bunch spacing in bunch trains. Encouraged by this progress, we propose three-dimensional profile monitor based on a femto-second pulse storage optical cavity: experimental results using pico-second pulse and design of femto-second profile monitor will be reported in this paper.

PICO-SECOND DEMONSTRATION AT LUCX ACCELERATOR

Experimental Setup

LUCX multi-bunch electron linac is located by the side of the KEK-ATF accelerator. Figure 1 shows experimental setup of LUCX. The electron beam parameters are also shown in Table 1. As shown in Figure 1, the accelerator

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† kazuyuki.sakaue@aoni.waseda.jp
‡ present address:Okayama University

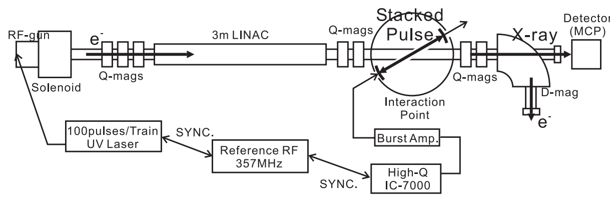

Figure 1: LUCX electron beam line.

Table 1: Parameters of Multi-bunch LINAC

Charge	Energy	Num. Bunch	Bunch Space
0.4nC	43 MeV	100/Train	2.8nsec

consists of a photo-cathode RF-Gun and 3m-long linac to generate and accelerate a multi-bunch electron beam up to 43 MeV. Beam loading effect in the accelerating structure is compensated by adjusting the timing of rf pulse, then the energy difference in a bunch train is compensated less than 1% at 43 MeV[6]. It is noted that LUCX accelerator has only one klystron for exciting rf-gun and accelerating tube, thus the beam loading is compensated totally in both accelerating structures. After acceleration, laser-electron interaction point is located between the doublet quadrupole magnets to focus at the interaction point and to re-focus a diverging electron beam. At the interaction point, pulsed-laser super-cavity is installed at an angle of 20 deg with beam line, which can produce a high peak and high average power photon target. Downstream of the interaction point, electrons are bended toward the earth by a right-angle analyzer magnet to separate from the scattered photons and dumped after an energy monitor system. According to the distance from interaction point to X-ray detector and the aperture of Be window, X-rays within 10mrad scattered angle can be extracted from the vacuum. The X-ray detector is located after the Be window. We chose a Micro-Channel Plate (MCP: F2224-21 Hamamatsu Photonics K. K.) in this experiment because of its time resolution. It enables us to measure the X-ray pulse-train pulse-by-pulse.

As a photon target, we have been developing the high finesse super-cavity[7]. In pulsed-laser storage case, the length of mode-locked cavity and super-cavity must be equal with less than nano-meter accuracy on more than 1000 finesse cavity so that each cavity lengths have to be fed back. In this development, we devised a "burst mode super-cavity", that is a technique of pulsed amplified laser stacking in the super-cavity as shown in Figure 1 and 2. This technique provides high power pulse when the electron bunch-train comes to the interaction point, that is suitable for linac electron beam. Figure 2 shows the timing diagram of burst mode cavity and LUCX multi-bunch electron beam. To inject a pulse-amplified laser pulses, laser power in cavity has higher peak power at the pumping timing (Figure 2). To synchronize a pumping timing to the electron bunch train, the number of X-ray will be enhanced by the gain of laser amplifier.

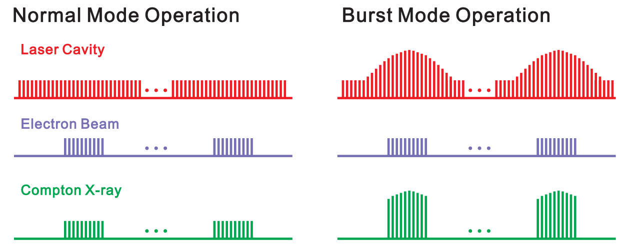

Figure 2: Timing diagram of burst mode cavity and electron linac.

The measured parameters of burst mode super-cavity is shown in Table 2. We have already succeeded in the burst mode cavity operation and achieved more than 100 µJ/pulse energy in the cavity.

Table 2: Parameters of Burst Mode Super-cavity

Pulse Duration	Finesse	Waist size	Pulse Ene.
7-psec (fwhm)	878.5	30.3 µm	110 µJ

As described in Figure 1, stored pulse laser and cathode illuminating UV laser, which produces electron bunches, are synchronized to same reference rf signal with about 1psec accuracy, therefore the pulse spacing and electron bunch spacing might be same without any other effects (see next section for detail).

Experimental Results

In LUCX, we are expecting to generate 33keV 100 pulses/train X-rays using 43 MeV multi-bunch electrons and 1064nm laser light. We have already succeeded in generating and characterizing the laser-Compton X-rays[8]. Using MCP detector, the X-ray pulse-train can be measured as shown in Figure 3. This figure was obtained by subtracting the background waveform from the raw MCP signal. 100 X-ray pulses were separately detected in 280nsec, which is consistent with the electron bunch train.

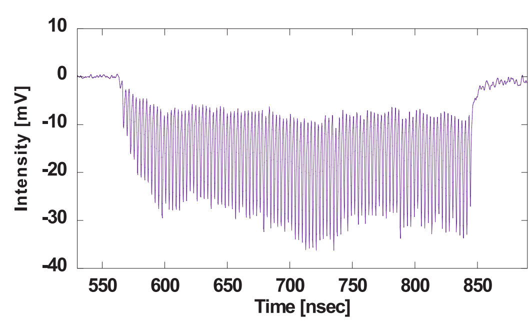

Figure 3: Pulse-train x-rays detected by MCP.

Scanning the laser target position or laser pulse timing with acquiring the peak intensity of each X-ray pulses, the bunch-by-bunch electron beam profile measurement can be achieved. This method will provide not only a bunch-by-bunch electron beam profile, but also information on bunch spacing distributions.

We firstly scanned the laser position both vertical and horizontal direction for measuring the multi-bunch electron beam profile. The results of vertical position scan and hor-

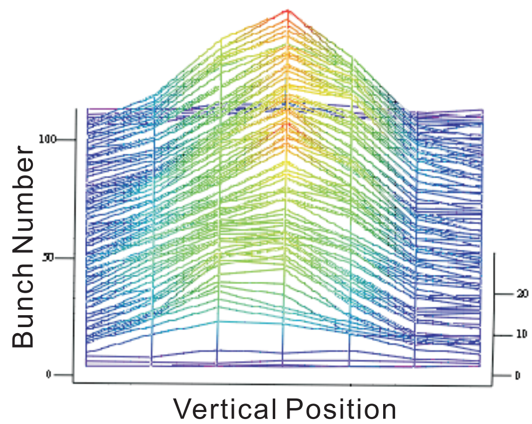

Figure 4: Vertical position scan.

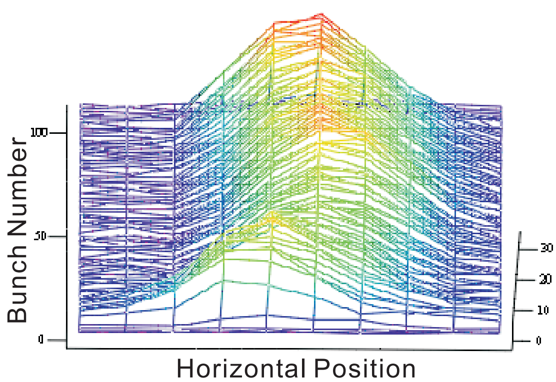

Figure 5: Horizontal position scan.

izontal scan are shown respectively in Figures 4 and 5. As shown in Figure 4, the optimum colliding position was almost the same in all of the bunches, but the X-ray intensity from the former bunches was lower than that from the latter bunches. We believe that this phenomenon was caused by the bunch spacing narrowing as described below.

Figure 5 shows the result of horizontal scanning. The optimum horizontal position differed for each bunch. When beam convergence isn't strong, the horizontal position shift Δh can be compensated by collision timing shift Δt as:

$$\Delta h = (\beta c \Delta t + \cos\theta)\sin\theta \qquad (1)$$

where β is the Lorentz factor, c is light velocity, and θ is the collision angle. Thus, the optimum position shift is regarded as the shift of the optimum collision timing.

In order to define the cause of this optimum position difference, we performed a bunch-by-bunch timing profile measurement. Timing profiles are shown in Figure 6.

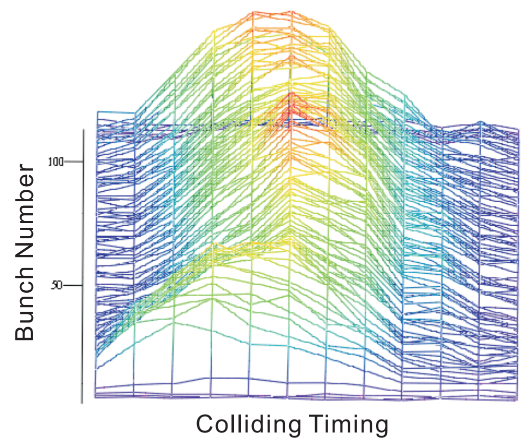

Figure 6: Collision timing scan.

Profiles are almost identical to those shown in Figure 5. As I mentioned above, LUCX accelerator uses only one klystron to excite both the rf-gun cavity and accelerating tube. Further, the beam-loading effect is compensated for using both the rf-gun cavity and accelerating tube. Therefore, the electron bunches have slightly different energy at the output of the rf-gun cavity. This causes velocity dispersion, and results a bunch spacing shifting. In the case of LUCX, the former bunches have slightly lower energy than the latter bunches, hence the bunch spacing is narrowed by the velocity dispersion. Figure 7 illustrates the

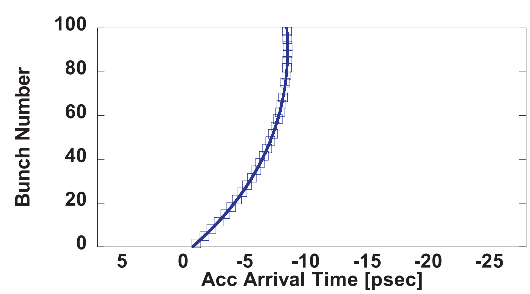

Figure 7: Acc. arrival time calculation.

calculated difference in the accelerating tube arrival time for each electron bunch. A difference of about 10psec is calculated in the whole bunch train. The horizontal axis of Figure 7 is same with Figure 6, as it is clearly found that the experimental results show good agreement with calculation. Also, the optimum horizontal position shift in Figure 5 was consistent with this timing shift.

DESIGN OF FEMTO-SECOND PROFILE MONITOR

We demonstrated a pico-second 3-dimensional profile monitor using pulse storage optical cavity. The transverse and longitudinal profile can be measured for each bunches in multi-bunch electron beam. Further more, the bunch spacing narrowing was observed in the LUCX multi-bunch electron beam due to the velocity dispersion.

Encouraged by this successful results, we started to design a femto-second profile monitor using pulse storage optical cavity. This monitor has many advantages, such as non-destructive, possibility of measuring the transverse and longitudinal profile, and bunch spacing distribution. However, there are some disadvantages, such as disability of single shot measurement.

The resolution of this monitor is determined by both laser pulse profile and electron beam profile. Here we assume the colliding angle θ (in the X-Z plane) and scan the laser pulse timing, the convolution width of electron-laser crossing is given by:

$$\sigma = \sqrt{(\cos\theta + 1)^2(\sigma_{eX}^2 + \sigma_{lX}^2) + \sin^2\theta(\sigma_{eZ}^2 + \sigma_{lZ}^2)} \quad (2)$$

where σ is a measured profile width, σ_{eX} an electron horizontal beam size, σ_{eZ} a bunch length, σ_{lX} a laser horizontal size, and σ_{lZ} a pulse duration. We can find in Equation 2, obtusely crossing provides us to measure longitudinal electron profile with light affect by electron and laser beam transverse profile.

Figure 8 shows the calculated result of expected crossing width as a function of electron bunch length. In this calculation, parameters of electron beam and laser were assumed as shown in Table 3. Vertical axis of Figure 8 is a ratio of measured profile (σ) and other profile width (except bunch length) as a function of rms bunch length. Larger value in Figure 8 means smaller contaminations from horizontal profile. Looking at Figure 8, the phenomena expected by Equation 2 is found. The obtuse crossing angle provides us a smaller effect on the expected measured profile. At the view of colliding angle of more than 160deg, this monitor has a feasibility of measuring hundreds femto-second bunches.

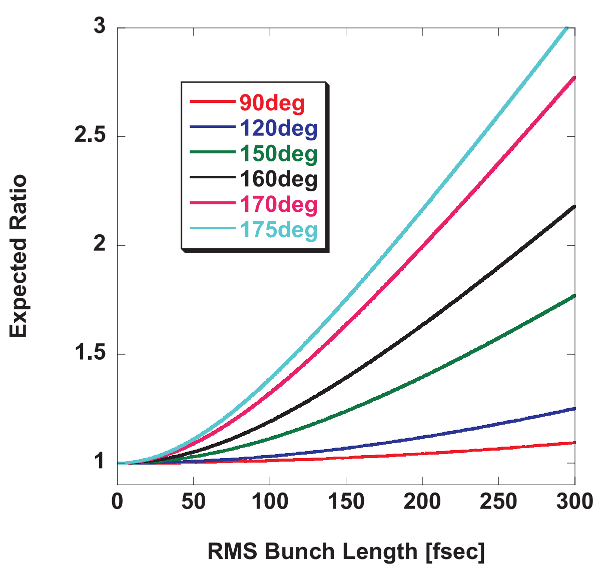

Figure 8: Crossing angle dependence of femto-second bunch measurement.

Table 3: Parameters of Electron-Laser Pulse

σ_{eX}	σ_{eZ}	σ_{lX}	σ_{lZ}
200 µm	Variable	20 µm	100 femto-sec

CONCLUSIONS AND PROSPECTIVE

We have demonstrated a pico-second profile monitoring by using pulse laser storage cavity and investigated that this monitor can measure not only the electron beam profile but also bunch spacing of the electron bunch train. Storing femto-second laser pulses in the optical cavity, femto-second profile measurement will be realized in the calculation.

However, resolution of this monitor strongly depends on signal-to-noise ratio of laser-Compton X-ray and background from accelerator, timing jitter of each pulses, beam size/position jitter and so on. Now, we cannot calculate a temporal resolution of this monitor. Therefore, this scheme should be optimized for the real accelerator and all the parameters which influences to temporal resolution have to be developed for the ultra-short bunch measurement. In the near future, we will demonstrate a femto-second pulse storage and its pulse duration measurement.

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