DEMONSTRATION OF MULTI-PULSE X-RAY GENERATION VIA LASER-COMPTON SCATTERING USING PULSED-LASER SUPER-CAVITY*

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Abstract

A compact and high quality x-ray source is required for various field, such as medical diagnosis, drug manifacturing and biological sciences. Laser-Compton based x-ray source that consist of a compact electron storage ring and a pulsed-laser super-cavity is one of the solutions of a compact x-ray source. Pulsed-laser super-cavity has been developed at Waseda university for a compact high brightness x-ray source. The pulsed-laser super-cavity enables to make high peak power and small waist laser at the collision point with the electron beam. 357 MHz mode-locked Nd:VAN laser pulses can be stacked stably in a 420 mm long Fabry-Perot cavity with "burst mode", which means stacking of electron beam synchronized amplified pulses in our R& D. In view of this successful result, we have started an X-ray generation experiment using a super-cavity and a multi-bunch electron beam at KEK-LUCX. Recently, the demonstration experiment between the burst mode pulsed-laser super-cavity and the 100 bunch multi-bunch electron beam is successfully performed. Development of the super-cavity and the experimental results of X-ray generation will be presented at the conference.

INTRODUCTION

Recently, x-rays from synchrotron radiation (SR) is widely used and produced a number of results in various fields, for example, medical diagnosis, biological sciences, material sciences and so on. However, SR x-rays is generated by the huge facility as SPring-8, therefore the use is limited by the operation schedule and the number of users. On these backgrounds, a compact x-ray source has been strongly required and studied in many laboratories. In 1997, Huang and Ruth proposed a compact laser-electron storage ring (LESR) for electron beam cooling or x-ray generation.[1] In this proposal, each electrons and photons storage 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 have developed a laser cavity system as a laser-wire beam profile monitor for measuring the electron-beam emittance at KEK-ATF.[2] We proposed to apply this 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.[3] On the other hand, to use a multi-bunch electron linac and a "burst mode" super-cavity (see Sec. 3), high peak power laser target can be produced, which synchronized with a multi-bunch electron beam, so that linac based compact x-ray source is also readily achievable.

As the first step, we are performing a proof-of-principle experiment of laser-Compton scattering between pulsed-laser super-cavity and multi-bunch electron beam. We call this linac based x-ray source, "LUCX" (Laser Undulator Compact X-ray source).

LUCX ELECTRON ACCELERATOR

LUCX multi-bunch electron linac is built by the side of the KEK-ATF accelerator. Figure 1 shows the beam line layout of LUCX. As shown in Figure 1, the accelerator

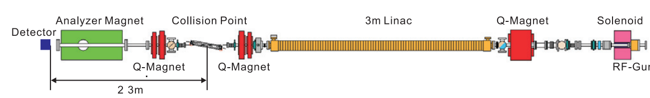

Figure 1: LUCX Electron Beam Line

consists of a photo-cathode RF-Gun and 3 m-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 and so the energy difference in a bunch train is compensated less than 1%.[4] The parameters of a multi-bunch electron linac is shown in Table 1.

Table 1: Parameters of Multi-bunch LINAC

Bunch Charge	Energy	Num. Bunch	Rep Rate
0.4 nC	43 MeV	100/Train	12.5 Hz

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

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peak and high average power photon target. The detail parameters of the super-cavity are described in following section. Downstream of the interaction point, electrons are bended toward the earth by a right-angle analyzer magnet to separate from the scattered photons and damped after an energy monitor system. According to the distance between interaction point and x-ray detector and the aperture of Be window, x-rays within 10 mrad scattered angle can be extracted from the vacuum.

PULSED-LASER SUPER-CAVITY

We have been developing the high finesse super-cavity to be used in this project.[5] In pulsed-laser 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. We have already succeeded in stacking 2.5 kW power in cavity and operating more than 1900 finesse super-cavity system over 10 hours without failing the resonant feedback.[6]

Taking over this successful result, we devised and developed a "burst mode super-cavity", that is a technique of pulsed amplified laser stacking in the super-cavity. Figure 2 shows a diagram of burst mode cavity and Figure 3 shows the timing diagram of burst mode cavity and LUCX multi-bunch electron beam. As shown in Figure 2, mode-locked

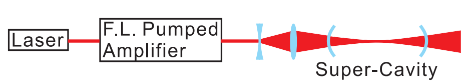

Figure 2: Diagram of Burst Mode Super-Cavity

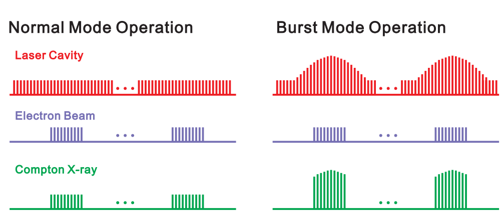

Figure 3: Timing Diagram of Burst Mode Cavity System

laser is amplified by the flash lamp pumped (pulse flash pumping) amplifier before injected to the super-cavity. To inject a pulse-amplified laser, laser power in cavity has high peak power at the pumping timing (Figure 3) and to synchronize a pumping timing to the electron beam timing, the number of x-ray will be enhanced by the gain of laser amplifier.

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 40 kW peak power in the cavity.

Table 2: Parameters of Burst Mode Super-Cavity

Amp Gain	Finesse	Waist size	Peak Power in Cav.
70	878.5	30.3 µm	40 kW

X-RAY GENERATION EXPERIMENT

Expected X-ray at LUCX

In LUCX, we are planning to generate 33 keV multi-pulse x-rays using 43 MeV multi-bunch electrons and 1064 nm laser light in the super-cavity. To scatter the laser photon off the electron beam at an angle of 20 deg, the generated x-rays in a front scattered angle have the energy of around 33 keV, that the attenuation coefficient of iodine is sharply changed (K-edge). In medical application, around 33 keV x-ray is used for a contrast diagnosis.

Considering the number of generating photons, to use burst mode super-cavity for laser-Compton collision at LUCX, the number of produced x-ray is multiplied by the peak power in the cavity. According to the parameters in Table 1, 2, the expected number of x-ray is 1.56×10^4 Photons/train in total. As the results of background measurement, this value is enough for x-ray detection.

Laser-Compton X-ray Detection

X-ray Detector Figure 4 shows the setup of the x-ray detector at LUCX. Detection system consists of 5mm radius collimator and scintillation detector. We produced a 150 µm thick LYSO scintillation detector to detect x-ray signal, which is not sensitive for high energy photons and has relatively high time resolution (40ns). According to this detector setup, the aperture of detector is about 1 mrad and expected number of detected x-ray is 2.0×10^2 Photons/train.

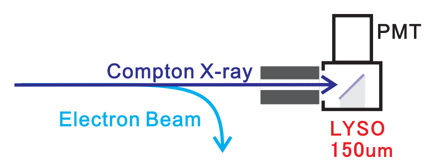

Figure 4: X-ray Detection System at LUCX

Timing & Laser Power Correlation We have already performed an x-ray generation experiment using a burst mode cavity, multi-bunch electron beam and a scintillation detector (Figure 4). The experimental results of x-ray detection are shown in Figure 5 and 6 As shown in Figure 6, the number of x-ray is certainly proportional to the laser power. On the other hand, Figure 5 shows the timing cross correlation between an electron beam and a laser pulse, to scan the laser timing at the collision point. The gaussian fit of the experimental result is also appeared in the figure (dotted line) and the rms of fitted line is 0.97 deg (7.5 ps) which is consistent of an electron bunch length. These two results indicate that this signal is exactly produced by the laser-Compton scattering between the multi-bunch beam and the pulsed-laser super-cavity. Concerning the number

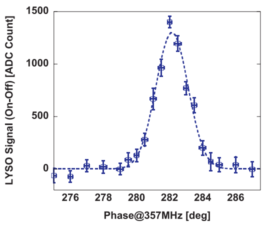

Figure 5: Timing Correlation

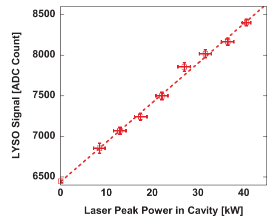

Figure 6: Laser Power Correlation

of produced x-rays, according to the calibration of LYSO scintillation detector, 1.65×10^2 Photons/Train have been detected at 40 kW peak laser power in super-cavity. This number is consistent with the expected number of x-rays of 2.0×10^2 Photons/Train

Vertical Beam Size Measurement The waist size of the laser target is precisely determined by the mirror curvature and the cavity length in super-cavity, so that scanning the position, measured x-ray profile can be used as the electron beam size measurement. Figure 7 shows the result of laser target position scan. The gaussian fit of the

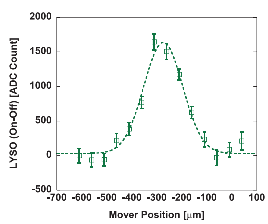

Figure 7: Vertical Laser Position Scan

result is shown by dotted line and the rms of x-ray profile is 77.6 μm. As described in previous section, laser waist size is measured as 30.3 μm. To consider the laser waist, beam size of the electron beam is calculated to 71.4 μm.

X-ray Energy Measurement

After detecting the laser-Compton x-ray, we performed an x-ray energy measurement using a bragg reflector (periodic crystal). The setup of x-ray energy measurement is shown in Figure 8. HOPG (Highly Oriented Pyrolytic

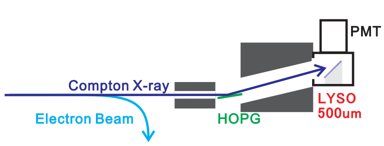

Figure 8: Setup of X-ray Energy Measurement

Graphite) is located after the collimator as the bragg reflector, which has the lattice period of $d = 3.356$ Å. Here, the x-ray energy can be decided by the bragg law (Eq. 1).

$$\lambda = 2d \sin\theta \quad (1)$$

where λ, d and θ indicate the wavelength of x-ray, a lattice distance and a glancing angle at maximum reflectivity, respectively. Moreover, HOPG has another advantage, such as larger integrated reflectivity because of its mosaicity so that larger x-ray signal can be achieved at the LYSO detector.

The result of x-ray energy measurement is shown in Figure 9 as a function of electron beam energy. The energy

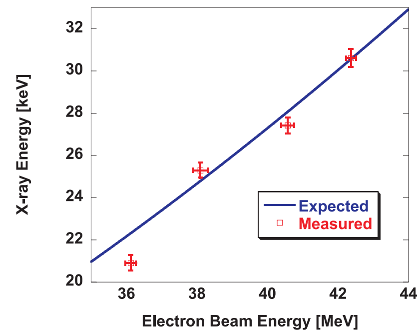

Figure 9: Result of X-ray Energy Measurement

measurement was performed at several electron beam energy, 36, 38, 40 and 42 MeV. The measured plots (red plots) show good agreement with the blue line which indicates the expected x-ray energy as a function of beam energy.

CONCLUSIONS

We demonstrated a multi-pulse x-ray generation using pulsed-laser super-cavity and multi-bunch electron linac and confirmed the x-ray is certainly generated from the process of laser-Compton scattering by observing the correlation of laser-electron crossing. Further more, the energy of x-ray photon was measured by the reflection angle of bragg crystal and the results were consistent with the calculation.

In future, we will study about the effect of multi-bunch acceleration, and will design and construct a compact x-ray source for practical use, considering both warm and cold linac.

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