GENERATION OF MULTI-BUNCH BEAM WITH BEAM LOADING COMPENSATION BY USING RF AMPLITUDE MODULATION IN LASER UNDULATOR COMPACT X-RAY (LUCX)

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Abstract

We have been developing a compact X-ray source based on inverse Compton scattering (ICS) between an electron beam and a laser pulse stacked in an optical cavity at Laser Undulator Compact X-ray (LUCX) accelerator in KEK. The accelerator consists of a 3.6-cell photo-cathode rf-gun, a 12-cell standing wave accelerating structure and a 4-mirror planar optical cavity. Our aim is to obtain a clear X-ray image in a shorter period of times and the target flux of X-ray is 1.7×10^7 photons/pulse with 10% bandwidth at present. To achieve this target, it is necessary to increase the intensity of an electron beam to 500 nC/pulse with 1000 bunches at 30 MeV. Presently, we have achieved the generation of 24 MeV beam with total charge of 600 nC in 1000 bunches with the bunch-by-bunch energy difference is within 1.3% peak to peak. The beam-loading has been compensated by injecting the beam before rf power has been filled (ΔT method) and by modulating the amplitude of the rf pulse. We report the results of the multi-bunch beam generation and acceleration in the LUCX accelerator.

INTRODUCTION

X-rays are applied to various area of application, such as medical application, biological science, material science etc. Synchrotron radiation which is generated by GeV order storage rings is commonly used as high brightness X-ray sources. However the rings are generally huge and expensive. On the other hand, an X-ray source based on ICS can be compact and inexpensive compared with its rings because this method can produce X-rays with the same energy by utilizing an electron beam with the lower energy by the rings about two orders of magnitude. However this method requires more development.

In order to develop a compact X-ray source based on ICS for X-ray imaging, we have constructed the LUCX accelerator at KEK. X-rays are generated by ICS between a multi-bunch electron beam with the energy of 24~40 MeV and a laser pulse with the wavelength of 1064 nm in this accelerator.

UPGRADE OF LUCX ACCELERATOR

X-ray imaging experiments have been started here since the autumn of 2011. We have succeeded to take the X-ray image of fish bone [1] so far. However, it took two

hours to get this image due to low intensity of X-ray with 10^4 photons/pulse. Therefore we have upgraded this accelerator to increase the intensity of X-rays in 2012. A 3.6-cell rf-gun, a 12-cell booster and a 4-mirror planar optical cavity have been installed and commissioned. The X-ray generation and the X-ray imaging are already started after upgrade [2]. The number of bunches has been extended from 150 bunches to 1000 bunches now. Table 1 shows the present and the design parameters of an electron beam. The target intensity of X-rays is 1.7×10^7 photons/pulse 10%b.w. at the energy of 15keV in this upgrade.
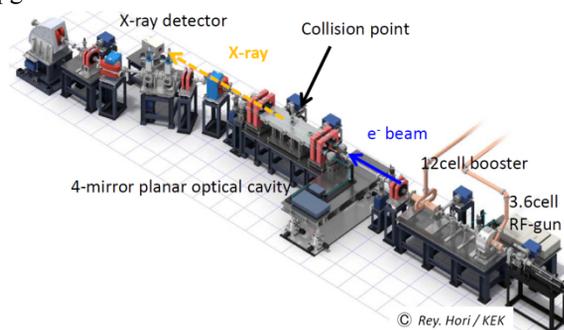
Figure 1: The beamline of the LUCX accelerator.

Table 1: Present and Design Parameters of Electron Beam

	Present	Design
Energy	24MeV	30MeV
Intensity	0.6nC/bunch	0.5nC/bunch
Number of bunch	1000	1000
Beam size (rms)	80μm x 50μm	33μm x 33μm
Pulse length(FWHM)	15ps	15ps

LUCX ACCELERATOR

The the LUCX accelerator is shown in Fig. 1. A 3.6-cell photo-cathode rf-gun generates an electron beam with the energy of 10 MeV and then the beam is accelerated to 30 MeV by a 12-cell booster. After that, the beam is collided with a laser pulse in a 4-mirror planar optical cavity and then X-rays are generated by ICS. The electron beam is separated from the X-ray by a bending magnet and then is dumped to the beam dump. The X-rays are extracted from a beamline through a Be window with the thickness of 300 μm and then detected by either a micro-channel plate (MCP) or an SOI imaging sensor [3].

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Figure 2 shows the cut view of the S-band 3.6-cell rf-gun [4] which has been developed on the basis of the 1.6-cell rf-gun of BNL-GunIV [5]. The number of cavities is increased from 1.6-cell to 3.6-cell to increase the energy and then the cavity structure consists of smooth curves to increase the Q-value of the cavity and to reduce a dark current from the surface. Cesium telluride (Cs_2Te) film is evaporated on the surface of the Mo cathode plug. An electron beam is emitted from the cathode by irradiating 266 nm laser light. A generated electron beam is accelerated to 10 MeV at here.
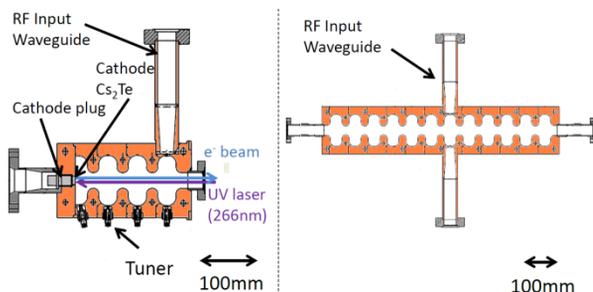
Figure 2: The left cut view is a 3.6-cell photo-cathode rf-gun and the right one is a 12-cell booster.

The cut view of the 12-cell booster [4], which is standing wave accelerating tube, is shown in Fig. 2. The structure of the cavity is almost the same as that of the rf-gun. An rf pulse is inputted through two input ports to reduce the discharge at the coupler and to obtain symmetrical electric field in a coupling cavity. The parameters of the 12-cell booster are shown in Table 2. An electron beam is accelerated to from 10 MeV to 30 MeV here.

Table 2: Parameters of the Rf-gun and the Booster

	3.6-cell rf-gun	12-cell booster
Frequency	2856 MHz	2856 MHz
Q-value	15000	17800
Coupling β	0.99	1.1
R/Q	395 Ω	420 Ω
Mode separation	2.8 MHz(π-2/3π)	1 MHz(π-10/11π)
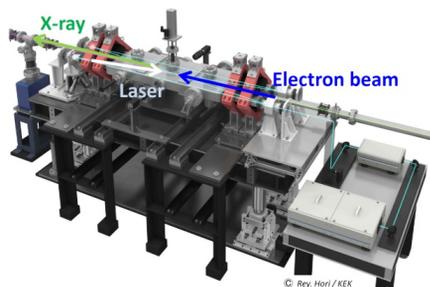
Figure 3: A four-mirror planar optical cavity.

A four-mirror planar optical cavity [2] is a four-mirror bow-tie ring resonator. The drawing is illustrated in Fig. 3.

The cavity enhances the laser power and makes small laser size at the collision point. The spacing of laser pulses is equal to that of electron bunches. Therefore the laser pulses can collide with all bunches of multi-bunch electron beam. The distance between the concave mirrors has been enlarged to 1.8m to enhance the stored power and to increase the laser size on the mirror because the stored power is limited by the damage threshold of the mirrors.

RF SYSTEM FOR SYNCHRONIZATION

The master clock of 357MHz for synchronization is generated from the signal of laser pulses injected to the optical cavity in this accelerator. We call this method the laser master system, whose diagram is shown in Fig. 4. The frequency of the rf signal delivered to klystrons is converted from 357MHz to 2856MHz and then cut out as a rectangular wave. The amplitude of the pulse is modulated by an Inphase-Quadrature (IQ) modulator in order to compensate the beam loading effect. The modulated pulse is injected to a klystron after amplified.
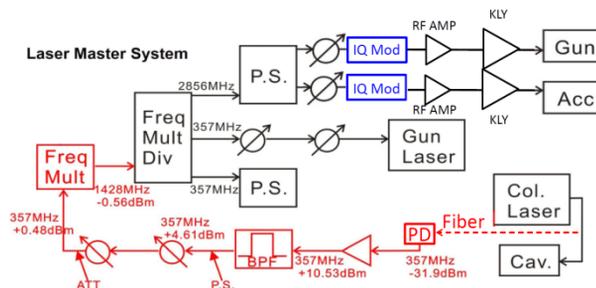
Figure 4: The diagram of the laser master system.

The length of the optical cavity must be held in the accuracy less than nanometre to keep resonance and must also be synchronize to the bunch spacing of an electron beam. The former is satisfied by controlling the length of the cavity of the injection laser device (internal cavity) and the latter the length of the cavity installed on the beamline (external cavity). Two different feedback systems have to run to keep the both conditions if the other master clock such as a signal generator is used. In this case, it is difficult to keep their feedbacks stably because the length of the internal cavity has to be changed while keeping resonance when the external cavity is changed by the feedback. In the laser master system, we need only one feedback system which can concentrate to keep resonance. Therefore the stability of the stored power in the cavity has been improved very much by using this method. The rf frequency of the master clock is determined by the length of the external cavity and then the frequency of the accelerator devices such as klystrons synchronizes with this length.

MULTI BUNCH BEAM GENERATION

The beam loading compensation is important issue in case of accelerating a multi-bunch electron beam. The loading effect is compensated by injecting the beam in the

timing of the transition region when rf power is filled (ΔT method) [6]. The energy compensation is optimized by adjusting the timing between an electron beam and an rf pulse.

The bunch-by-bunch energy is evaluated by a bunch position at the downstream of the first bending dipole with its magnetic field strength.
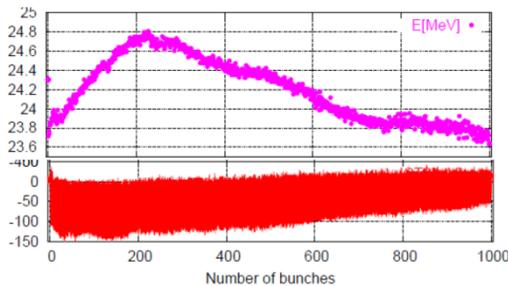
Figure 5: The beam energy when the beam-loading is compensated by ΔT method only.

Figure 5 shows the measured energy of a multi-bunch beam with total charge of 600nC in 1000 bunches when the energy is compensated by ΔT method. The energy difference is about 4% (peak to peak). The pulse length of the 1000bunches beam is 2.8μs which is far longer than the filling time of 0.8μs. The rf power is almost filled at the timing of 200th bunch in this case. Therefore the beam-loading of the 200th and the following bunches cannot be compensated by ΔT method. The compensation is not enough for us because the energy difference changes the beam size at the collision point. If the energy is different by 4 percent, the size is different by about 10%. The difference also causes beam-loss in a dispersion section such as a downstream section of a bending magnet.
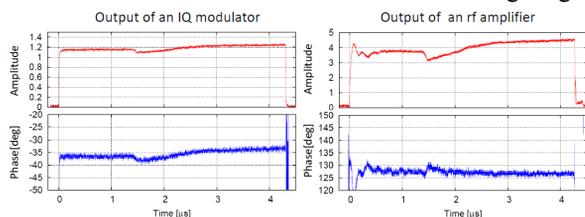
Figure 6: Amplitude and phase of An rf pulse after an IQ modulator(left) and an rf amplifier(right).

To improve the compensation, the amplitude of the rf pulse is modulated by an IQ modulator which can control amplitude and phase of the rf pulse. The rf signal is given by $A\cos(2\pi ft+\phi) = I\cos(2\pi ft) + Q\sin(2\pi ft)$ where A, I and Q is the amplitude of the rf pulse, in-phase ($I = A\cos\phi$) and quadrature ($Q = A\sin\phi$) respectively, f is the frequency of the rf signal and ϕ is the phase of the rf signal. Therefore we can modulate the amplitude and the phase of the rf pulse by controlling the inphase and the quadrature components whose pulses are generated by a function generator in our rf system.

The modulated rf pulse is shown in Fig. 6. The left and right graphs show the amplitude and the phase after the IQ modulator and the rf amplifier respectively. The IQ modulator modulates not only the amplitude but also the phase because the phase of the output pulse of the rf amplifier depends on the amplitude.

By combining both the ΔT method and the amplitude modulation, we have succeeded in generating the 1000 bunches electron beam with 600nC total charge at 24 MeV within the energy difference of 1.3%(peak-to-peak) as shown in Fig. 7.
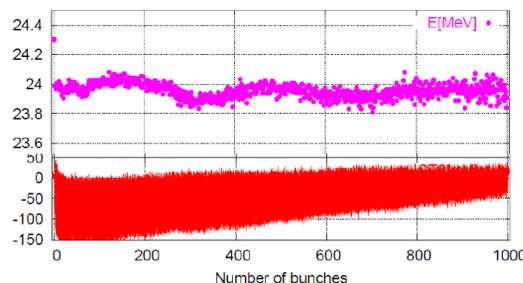
Figure 7: The beam energy when the beam-loading is compensated by both ΔT method and amplitude modulation.

The each bunch charge measured by a current transformer is also shown in Fig. 7. This decrease of the current reflects the time structure of laser pulses for generating the electron beam.

SUMMARY AND FUTURE PLAN

We have continued the tuning of the multi-bunch generation to increase the intensity after upgrade. Currently, the design current of the electron beam has been achieved as shown in Table 1. However the energy and the beam size at the collision point are not achieved to the design value. Therefore we have to continue the rf processing of the 3.6-cell rf-gun and the 12-cell booster to increase the rf power and the optimization of the optics to decrease the beam size. Then we will also try to obtain the clear X-ray images by using the SOI pixel sensor.

ACKNOWLEDGMENT

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