BEAM-LOADING COMPENSATION OF A MULTI-BUNCH ELECTRON BEAM BY USING RF AMPLITUDE MODULATION IN LASER UNDULATOR COMPACT X-RAY SOURCE(LUCX)*

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Abstract

We have been developing a compact X-ray source via laser Compton scattering(LCS) at Laser Undulator Compact X-ray source(LUCX) accelerator in KEK. In here, a multi-bunch electron beam is generated by a 3.6cell photo-cathode RF-gun and accelerated to 18-24MeV by a 12cell accelerating tube. And then 6-10 keV X-rays are generated by LCS between the beam and a laser pulse stored in a 4-mirror planar optical cavity. Presently, we have achieved the generation of 24MeV beam with total charge of 600nC in 1000bunches. The energy difference is within 1.3% peak to peak. The beam-loading is compensated by ΔT method and amplitude modulation of the RF pulse. However, there is the energy difference at the RF-gun. It is assumed that this causes the reduction of the X-ray flux due to change of the focused beam size. To reduce the energy difference, RF amplitude modulation is also applied to the RF pulse for the gun. The results of this beam-loading compensation will be reported.

INTRODUCTION

X-rays are used in a wide range of applications, for medical examination, biological science, material science and so on. High-flux and high-brightness X-ray is specially generated by synchrotron radiation storage rings with an order of GeV although they are generally large and expensive. On the other hand, an X-ray source via LCS is possible to generate X-rays with a similar energy by using a compact accelerator because the electron-beam energy is an order of tens of MeV. For example, 10keV X-rays can be generated by LCS with 24 MeV electron beam and a laser which wavelength is 1064 nm.

We have constructed a small electron accelerator called LUCX accelerator[1] at KEK in order to develop a compact X-ray source based on LCS. At here, 6-10 keV X-rays are generated by LCS of a multi-bunch electron-beam with the energy of 18-24 MeV and a laser pulse with the wavelength of 1064nm.

LUCX ACCELERATOR

The LUCX accelerator is an S-band normal conducting accelerator which consists of a 3.6cell photo-cathode RF-gun[2], a 12cell standing-wave accelerating tube[2] and a 4-mirror planar optical cavity[3]. The layout is shown in Fig. 1.

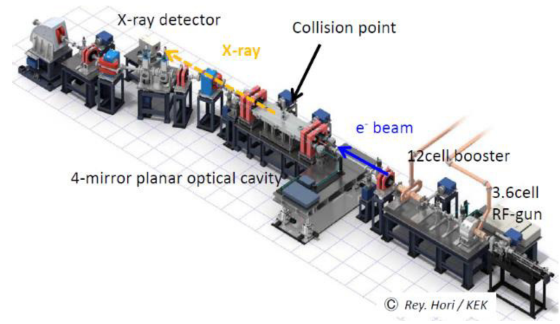

Figure 1: The beamline of the LUCX accelerator.

The RF-gun generates a 7.6MeV multi-bunch electron-beam with total charge of 600nC in 1000 bunches. The beam is accelerated from 7.6MeV to 24MeV by the accelerating tube. After that, the beam collides with a laser pulse stored in the optical cavity and then X-rays are generated by LCS. The beam is separated from the X-rays by the first bending dipole. X-rays are extracted to the air through a beryllium window with the thickness of 300μm.

Figure 2 shows the diagram of the RF system. 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. The frequency of the RF signal delivered to klystrons is converted from 357MHz to 2856MHz. And then the RF signal cut out as a rectangular wave. The pulse is injected to a klystron after amplified.

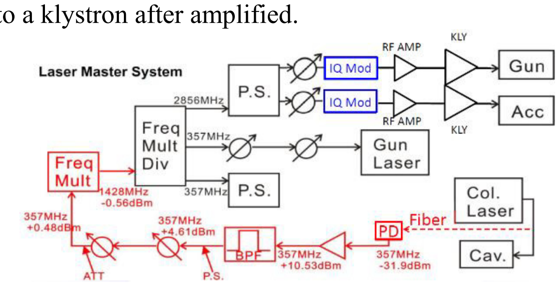

Figure 2: The diagram of the laser master system.

The amplitude of the pulse is modulated by an Inphase-Quadrature (IQ) modulator before the RF amplifier in order to compensate the beam loading effect which causes the energy reduction in a train on the acceleration of a multi-bunch beam. By modulating the amplitude of an RF pulse, the electric field for accelerating can be modified so that the energy reduction is cancelled out.

Two klystrons provide a 4.3μs RF pulse into the RF-gun and the accelerating tube respectively. The injected peak

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power into the RF-gun and the accelerating tube is 13MW and 23MW respectively at present.

The layout of the X-ray line is shown in Fig.3. A micro channel plate(MCP) and a photon-counting image-detector have been used as X-ray detector. The MCP(Hamamatsu F4655) is placed in the vacuum chamber on the X-ray line.

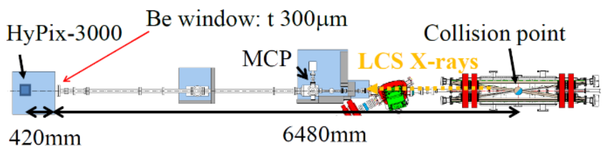

Figure 3: The setup of X-ray detectors.

BEAM-LOADING COMPENSATION

The beam loading compensation is important issue in the generation of a multi-bunch electron beam. Presently, a multi-bunch electron beam with 1000 bunches is generated in the LUCX accelerator. In ΔT method, before RF power is filled, the part where the amplitude of the electric field is rising is used to compensate the loading effect. However, the part is not used after RF power has been filled in the RF cavity. The pulse length of the 1000bunches beam is 2.8μs which is far longer than the filling time of 0.8μs. Therefore, the beam-loading of the 200th and the following bunches cannot be compensated by ΔT method.

Therefore, the loading effect is compensated by modulating the amplitude of the RF-pulse[4]. The amplitude is modulated by an IQ modulator which can control amplitude and phase of the RF pulse and which has been installed in the low level RF system(Fig. 2)[1].

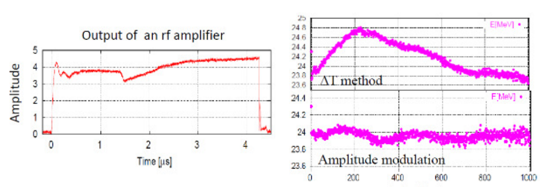

Figure 4: The modulated amplitude of the RF pulse and the bunch-by-bunch energy with the compensation by ΔT method only and by amplitude modulation respectively.

Figure 4 shows the result of the compensation by the amplitude modulation. The right graphs show the measured energy of a multi-bunch beam with total charge of 600nC in 1000 bunches. The bunch-by-bunch energy is evaluated by a bunch position at the downstream of the first bending dipole with its magnetic field strength. In the compensation by ΔT method, there is the energy difference in shown the upper graph. To correct this, the amplitude of the RF pulse is modulated like the left graph. After that, we have succeeded in reducing the energy difference within the energy difference of 1.3%(peak-to-peak).

However, in this case, there is the energy difference at the exit of the RF-gun because the amplitude modulation is applied to only the RF pulse of the accelerating tube. This energy difference causes the change of the focusing in the solenoid magnetic field. As a result, the change of the focusing makes the change of the beam size at the collision point. Therefore, the energy difference in a train of a multi-bunch beam could cause the uniformity of the signal of LCS X-rays in the train.

Actually, this uniformity of X-rays signal had been observed as shown in Fig. 5. This graph shows the signal of X-rays generated by LCS with 1000bunches electron beam with the total charge of 300nC and the signal of the beam current monitor. The signal strength of X-rays is not uniform although the signal of the beam current is uniform.

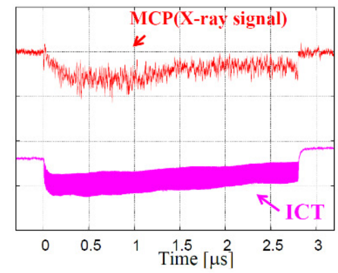

Figure 5: X-ray signal measured by MCP without amplitude modulation at the RF-gun.

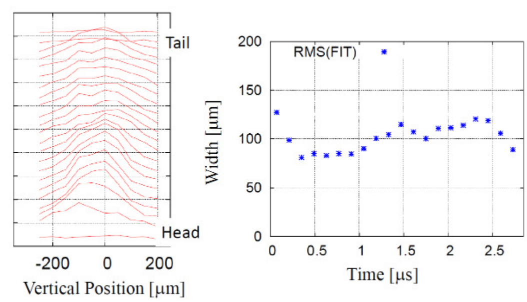

Figure 6: The result of the scan of the position between an electron beam and a laser pulse without amplitude modulation at the gun.

The beam profile data as shown in Fig. 6 was obtained from the waveform of X-ray signal measured by MCP. The plotted data of the profile is a mean value for each 50bunches of the pulse height of the waveform which was measured while scanning the relative position between an electron beam and a laser light. The change of the beam size in a train can be obtained from this measurement.

The beam size in a train had also changed as shown in Fig. 6. The left graph shows the beam profile of vertical direction in a train and the right graph shows that beam size evaluated from the profile by fitting with Gaussian.

The energy difference in a train at the RF-gun should be corrected to resolve the above-mentioned problem. Accordingly, we have to know the energy of a multi-bunch beam at the exit of the RF-gun. However, the energy cannot be measured directly because there is no bending dipole between the RF-gun and the accelerating tube. Therefore, the energy has been estimated as described below.

Firstly, the beam energy with 4bunches and 0.3nC/bunch was measured as changing the laser injection timing. The result is shown by the red points in Fig. 7. During this measurement, the RF power supplied to the accelerating tube was turned off. This energy is almost same as the multi-bunch beam energy without beam lading. Next, the energy reduction due to beam-loading was calculated in case of the charge of 0.3nC/bunch. This is shown by the purple line in Fig. 7. And then, the sum of the red one and the purple one becomes the estimated energy which is shown by the blue points in Fig. 7. This energy corresponds to the multi-bunch energy with beam loading. The peak-to-peak energy difference at the RF-gun is estimated 0.8MeV from Fig. 7.

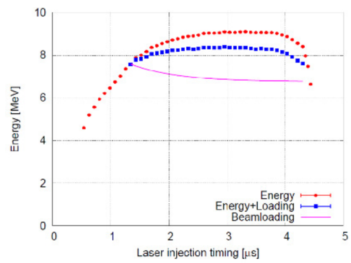

Figure 7: This graph shows an electron beam energy at the RF-gun without RF amplitude modulation.

The energy cancelling out the beam loading is calculated as shown by the blue points in Fig. 8. This is the target energy for the RF amplitude modulation. To achieve this energy, the RF amplitude modulation has been applied to an RF pulse supplied to the RF-gun. The modulation quantity is calculated by the relation between the energy and the amplitude of a RF pulse as shown by the left graph in Fig. 9. This modulation is applied to the RF pulse and, furthermore, the modulation quantity is optimized from the measured energy as shown by the right graph in Fig. 9. The red points in Fig. 8 are the optimized energy. The difference from the target energy could be kept within 0.07MeV.

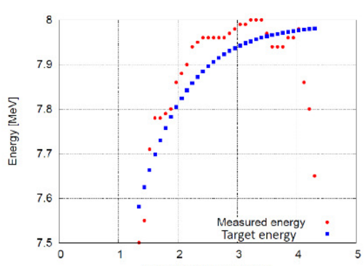

Figure 8: This graph shows an electron beam energy at the RF-gun with RF amplitude modulation.

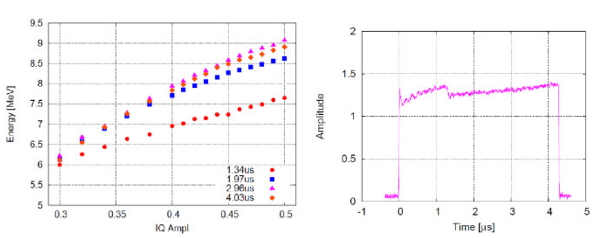

Figure 9: The electron beam energy as a function of RF amplitude at each laser injection timing and the modulated RF pulse shape after the RF amplifier.

We have tried to generate the LCS X-rays with the amplitude modulation of RF pulse for the RF-gun. The X-ray signal measured by the MCP is shown in Fig. 10. The uniformity of the X-ray signal in a train is clearly improved compared with the signal in Fig. 5. The beam profile and the beam size shown in Fig. 11 becomes also uniform in a train. The X-ray flux is 1.9×10^7 photons/sec. The flux normalized the intensity of the electron beam current and the laser power is 1.4 times more compared with the flux without the RF amplitude modulation for RF-gun.

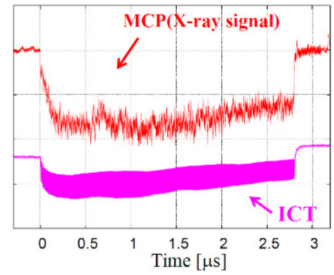

Figure 10: X-ray signal measured by MCP with RF amplitude modulation at the RF-gun.

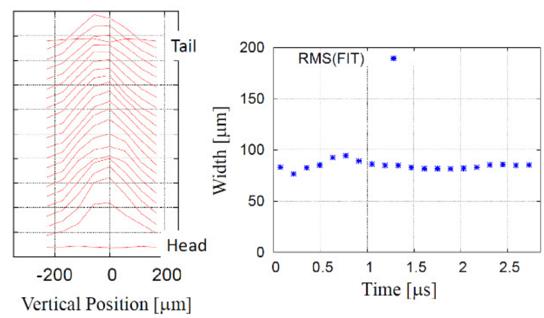

Figure 11: The result of the scan of position between an electron beam and a laser pulse with RF amplitude modulation at the RF-gun.

SUMMARY

We have been developing the compact X-ray source with a small electron accelerator and an optical laser cavity. The improvement on the generation of LCS X-ray has been successfully conducted by applying the beam-loading compensation at the RF-gun with the amplitude modulation. To increase the X-ray flux, further optimizations on an electron beam and an optical cavity has been continued by improving the intensity and the focal size at the collision point.

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