IMPROVEMENT OF X-RAY GENERATION BY USING LASER COMPTON SCATTERING IN LASER UNDULATOR COMPACT X-RAY SOURCE (LUCX)

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Abstract

We have been developing a compact X-ray source based on the laser Compton scattering (LCS) at Laser Undulator Compact X-ray source (LUCX) accelerator in KEK. We have started to take X-ray images such as refraction contrast images and phase contrast imaging with Talbot interferometer. In this accelerator, 6-10keV X-rays are generated by LCS. An electron beam is produced by a 3.6cell rf-gun and accelerated to 18-24MeV by a 12cell accelerating tube. A laser pulse is stored in a 4-mirror planar optical cavity to enhance the power. To increase the flux of LCS X-rays, we perform an optimization of the beam-loading compensation, improvement of the intensity of an electron beam and a laser light at the collision point. We report the result of the X-ray generation in this accelerator.

INTRODUCTION

X-rays are utilized for a wide range of applications, for example, medical examination, biological science, material science and so on. High-flux and high-brightness X-rays are specially generated by synchrotron radiation storage rings at 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 at a similar energy by using a compact and an inexpensive 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 1064nm laser light.

We have been developing a LCS based X-ray source at the LUCX accelerator which has been constructed in KEK. In this accelerator, 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. X-ray imaging experiments including absorption and refraction contrast images have been conducted since 2012. Last year, studies on a phase contrast imaging with Talbot interferometer started. The visibility of the moire fringes was about 33%[1,2]. However, the exposure time was five hours which is too long for imaging. Therefore, we improved the collision tuning to increase the X-ray flux.

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LUCX ACCELERATOR

The LUCX accelerator is a normal-conducting electron-accelerator at S-band frequency. This accelerator comprises a 3.6cell photo-cathode RF-gun[3], a 12cell standing-wave accelerating tube[3] and a 4-mirror planar optical cavity[4]. The layout is shown in Fig. 1.

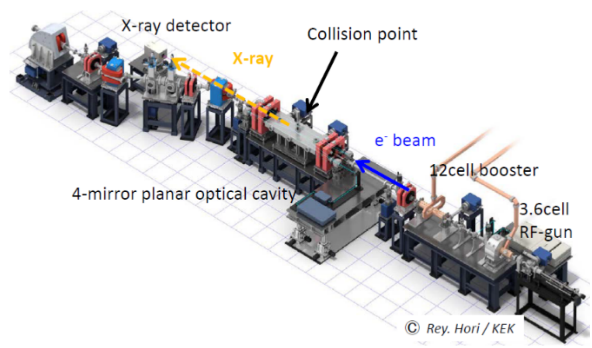

Figure 1: The beamline of the LUCX accelerator.

The RF-gun generates a 7.6MeV multi-bunch electron-beam with total charge of 600nC in 1000 bunches. And then, the accelerating tube accelerates the beam up to 24MeV. After that, the beam collided with a laser pulse stored in the optical cavity to generate X-rays by LCS. The scattered X-rays go straight through a beryllium window with the thickness of 300μm. On the other hand, the beam is separated from the X-rays by the first bending dipole and sent to the dump.

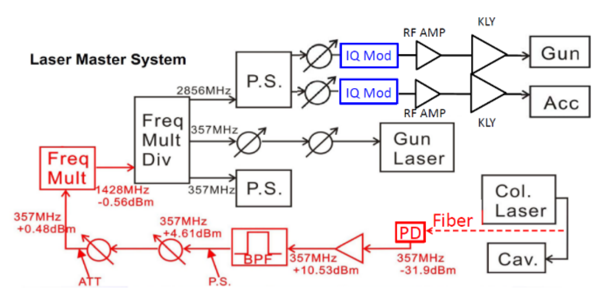

Figure 2: The diagram of the laser master system.

Figure 2 shows the diagram of the RF system. The 357MHz master clock is generated from the signal of laser pulses for the optical cavity. The devices in this accelerator is synchronized to this clock. We call this method the laser master system. The RF signal is delivered to klystrons after the frequency is converted from 357MHz to 2856MHz. And then the RF signal is chopped

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off into a rectangular wave by an Inphase-Quadrature (IQ) modulator which also modulates the amplitude of the pulse to compensate the beam-loading effect. The pulse is injected to a klystron after the amplification.

The beam loading effect 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 acceleration can be modified so that the energy reduction is compensated.

Two klystrons provide a 4.3μs RF pulse into the RF-gun and the accelerating tube respectively. The injected peak power into the RF-gun and the accelerating tube are 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 and measures the X-ray flux.

A HyPix-3000[5] which is a photon-counting image detector is installed at 6.9m from the collision point for taking X-ray images. This detector has a large active area of about 3000mm^2 (77.5x38.5mm^2) with a pixel size of 100x100μm^2.

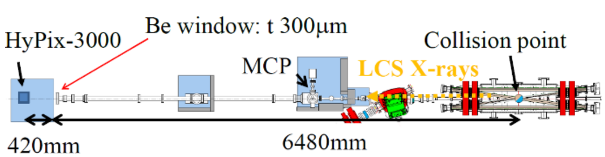

Figure 3: The setup of X-ray detectors.

Figure 4 shows the layout of the laser system for the RF-gun. The laser pulses with the wavelength of 1064nm are generated by a 357MHz Mode-locked laser device. And then, a thousand pulses which corresponds 2.8μs are cut out by the pockels cell and are amplified by two flash-lamp-pumped Nd:YAG amplifiers. After that, the wavelength is converted from 1064nm to 266nm by Beta barium borate (BBO) crystals. dump.

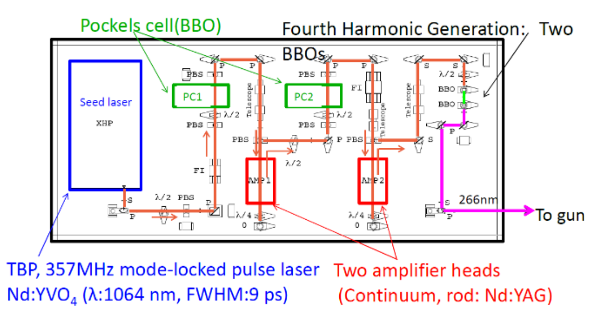

Figure 4: The layout of the laser system for the RF-gun.

IMPROVEMENT OF X-RAY GENREATION

Collision Tuning

We have improved the tuning of the collision between an electron beam and a laser pulse to increase X-ray flux.

First, In the tuning of the X-ray generation, the collision timing and the relative position between an electron beam and a laser pulse are scanned to find the point at which X-ray signal is maximized. Next, the focusing of the beam is also optimized by scanning the current of the solenoid and quadrupole magnets.

We observed that the X-ray signals in a train were not uniform as shown in the left graph of Fig. 5 although the above collision tuning is applied. This graph shows the signals of LCS X-rays measured by the MCP with the total charge of 300nC for 1000bunches, and the signals of the beam current monitor. The signal strengths of X-rays are not uniform although the signals of the beam current are uniform. It suggests that the beam size fluctuates inside a train.

In fact, the beam-loading compensation with the RF amplitude modulation at the RF-gun was not taken into account. Therefore, the energy difference in a train of a multi-bunch beam existed. Such the difference causes the change of the beam size because the focusing of the beam by a solenoid and quadrupole magnets changes. As a result, the energy difference caused the non-uniform fluxes of LCS X-rays in the train.

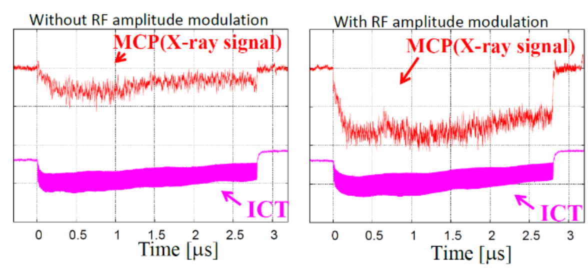

Figure 5: X-ray signal measured by MCP without and with amplitude modulation at the RF-gun respectively[8].

To make the flux uniform, the beam-loading has been compensated by using the RF amplitude modulation at the RF-gun[6]. The detail of the compensation is described in the reference of [7.8]. After the compensation, the peak-to-peak energy difference at the RF-gun can be reduced from 0.8MeV to 0.07MeV.

The X-ray signal measured by the MCP after this compensation is shown in the right graph of Fig. 5. The flat region of X-ray signals is extended compared with the signal in the left graph in Fig. 5. The X-ray flux normalized by the intensity of the electron beam current and of the laser power, is increased by a factor of 1.4 compared with that without the RF amplitude modulation for the RF-gun. The X-ray flux is 1.9x10^7 photons/sec in this case.

Figure 6 shows the absorption images of a red pepper. The left photograph was taken last year. The X-ray flux of 3.1x10^6 photons/sec which is the same flux when we tried a phase contrast imaging with Talbot interferometer last year[1,2]. The right photograph was taken recently. It becomes obviously bright compared with that taken last year. The flux is 1.8x10^7 photons/sec which is increased by a factor of 5.8.

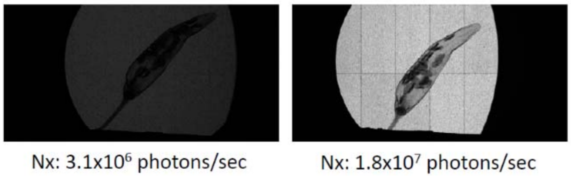

Figure 6: The absorption images of a red pepper taken by the HyPix-3000 last year and recently respectively.

Improvement of the Uniformity of the Bunch Charge in a Train

The reduction of the bunch charge in a train is observed as shown in the left graph of Fig. 7. If the bunch charge is different, the emittance growth by the space charge effect changes. Therefore, it is possible that the change of the beam size in a train is caused by the difference of the space charge effect, which becomes significant as the beam current increases.

The signal of laser pulse measured by a photodiode and the signal of electron beam measured by a current monitor for 1000 bunches are shown in Fig. 7. The amplitude of the signals decreases from the head region to the tail region because the head pulses takes the stored energy in the amplifier and reduces the population inversion for the pulses in the tail part. The reduction is about 51% at the tail end.

To avoid the reduction, we reduce the gain of the first amplifier. The result is shown in the right graph in Fig. 7. The reduction can be improved to 7%. However, the total charge of the electron beam is decreased from 600nC to 300nC. To recover the charge, we are trying to increase to the quantum efficiency of the Cs_2Te cathode in the RF-gun by re-evaporating Cs_2Te at present.

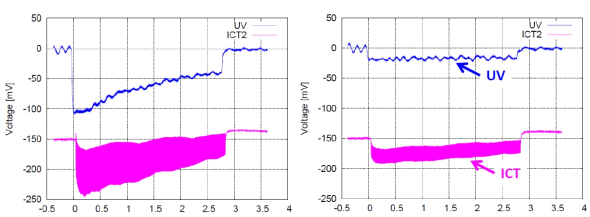

Figure 7: The signal of the laser light and the electron beam current before and after adjusting the laser gain respectively.

SUMMARY

We have been developing the compact X-ray source based on LCS with an optical laser cavity in the LUCX accelerator. The improvement on the generation of LCS X-rays was successfully achieved by applying the beam-loading compensation with the RF amplitude modulation. The uniformity of the bunch charge in a multi-bunch beam was also improved by adjusting the laser gain although we need to increase the quantum efficiency of the cathode on the RF-gun. Further optimizations to increase the X-ray flux are expected by increasing the intensity at the optical cavity and by optimizing the beam optics to make the focal size smaller at the collision point.

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