STATUS AND FUTURE PLAN OF THE DEVELOPMENT OF A COMPACT X-RAY SOURCE BASED ON ICS AT LASER UNDULATOR COMPACT X-RAY (LUCX)*

M. Fukuda#, S. Araki, A. Aryshev, Y. Honda, N. Terunuma, J. Urakawa, KEK, Ibaraki, Japan
K. Sakaue, M. Washio, RISE, Tokyo, Japan

Abstract

We have developed a compact X-ray source via inverse Compton scattering (ICS) between multi-bunch electron beam and a laser pulse stacked in an optical cavity at Laser Undulator Compact X-ray (LUCX) accelerator in KEK. Since the autumn of 2011, we have begun X-ray imaging test. In the beginning, it had taken two hours to get an X-ray image because of low intensity of X-ray with 10^4 photons/pulse. To get a clear X-ray image in a shorter period of times, we have upgraded the accelerator, which consists of a 3.6 cell photo-cathode rf-gun, a 12cell standing wave accelerating structure and a 4-mirror planar optical cavity. The target intensity of an electron beam is 500nC/pulse with 1000 bunches at 30 MeV. The one of laser pulse is also 6mJ/pulse. The expected number of X-ray is $1.7\text{x}10^7$ photons/pulse with 10% bandwidth. We have already started the multi-bunch beam generation and X-ray imaging test after upgrade. The accelerator produces 26.8 MeV beam with the total charge of 380nC in 300 bunches per pulse. The aging process is also continued to increase energy and intensity. We will report the results of the beam test and future plan of the development of a compact X-ray source at LUCX.

INTRODUCTION

X-rays have various fields of application, such as medial application, biological science, material science etc. Synchrotron radiation produced by GeV order storage ring is commonly used for high brightness X-ray source. However the device is generally huge and expensive. On the other hand, the X-ray source based on ICS is compact and inexpensive because this method can decrease this energy of an electron beam by more than an order of magnitude when producing X-rays with the same energy.

We have constructed the LUCX accelerator at KEK in order to develop the compact X-ray source based on ICS. Since the autumn of 2011, we have begun X-ray imaging test and succeeded to take the X-ray image of fish bone[1]. However, it took two hours to get the image due to low intensity of X-ray with 10^4 photons/pulse.

We have upgraded this accelerator in order to increase the intensity of X-rays in last year. The 3.6cell rf-gun, 12cell booster and 4mirror cavity have been designed and constructed for this upgrade. The X-ray generation and the X-ray imaging are already started after upgrade[2]. We will report the current status and future plan of the X-ray experiment in the accelerator.

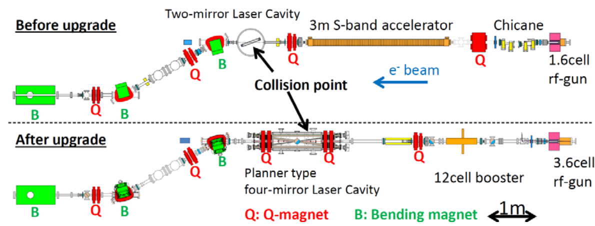

Figure 1: The beamline of the LUCX accelerator before/after upgrade.

LUCX ACCELERATOR

The upgraded beamline is shown in Fig. 1. A 3.6cell photo-cathode rf-gun generates an electron beam with the energy of 10MeV and then the beam is accelerated to 30MeV by a 12cell 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 X-rays are extracted into the atmosphere through a Be window with the thickness of 300μm. The electron beam is separated from the X-ray by a bending magnet and then is dumped to the beam dump.

3.6Cell Photo-Cathode Rf-Gun

An S-band 3.6cell rf-gun[3] has been installed instead of 1.6cell rf-gun to increase the beam energy. The cut view and the picture of the rf-gun is shown in Fig. 2. The cavity structure consists of smooth curves to increase the Q-value of the cavity and to reduce dark current from the surface. Cesium telluride (Cs_2Te) film is evaporated on the surface of the Mo cathode plug which is attached in the cavity by the load-lock system. An electron beam is emitted from the cathode by irradiating 266nm UV laser light. The beam is accelerated to 10MeV.

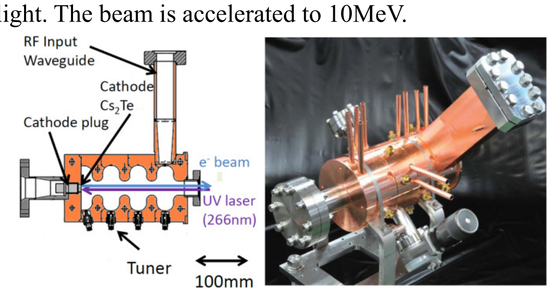

Figure 2: The cut view and the picture of 3.6cell rf-gun.

The cavity of the 3.6cell rf-gun has four resonance modes. Therefore the surface of the iris in the cavity has

*Work supported by the Quantum Beam Technology Program and Photon and Quantum Basic Research Coordinated Development Program of MEXT.
#mfukuda@post.kek.jp

reduced 3mm rather than former in order to expand the mode separation. The separation between 2/3π mode and π mode is 2.8MHz. The size of rf input port is also enlarged to adjust the coupling β to close to 1. Table 1 shows the parameter of the rf-gun.

12Cell Booster

A 12cell booster[3], which is standing wave accelerating tube, has been installed instead of an S-band travelling wave accelerating tube in order to downsize the accelerator section. The length has been shortened from 5.7 to 2.5m. An electron beam is accelerated to from 10MeV to 30MeV here.

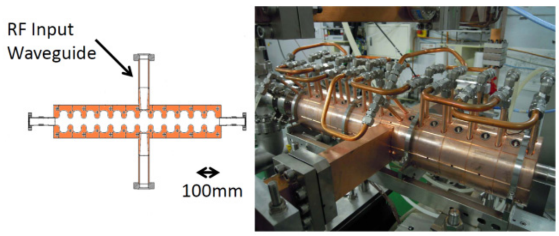

Figure 3: The cut view and the picture of the 12cell booster.

Figure 3 shows the cut view and the picture of the 12cell booster. The structure of the cavity is almost the same as that of the rf-gun. However, the accelerator has twelve resonant modes. Therefore the surface of the iris in the cavity has further reduced compared with that of the rf-gun to extend the mode separation. The separation between 10/11π mode and π mode is 1MHz. In addition, rf power is input through two input ports to obtain symmetrical electric field in a coupling cavity. The parameter of the 12cell booster is shown in Table 1.

Table 1: Parameters of the Rf-Gun and the Booster

	3.6cell rf-gun	12cell booster
Frequency(π-mode)	2856MHz	2856MHz
Q-value	15000	17800
Coupling β	0.99	1.1
R/Q	395Ω	420Ω
Mode separation	2.8MHz(π-2/3π)	1MHz(π-10/11π)

4-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. 4. 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.

To increase the luminosity of ICS by enhancing the stored power in the cavity and by bringing close to head-on collision, the 4mirror cavity is installed. The distance of the concave mirrors is made longer than former 2-mirror cavity to enhance the stored power and the laser size on the mirror is enlarged because the stored power is limited by the damage threshold of the mirrors. Moreover, the collision angle of an electron beam and a laser pulse is reduced to 7.5deg. The parameters are shown in Table 2.

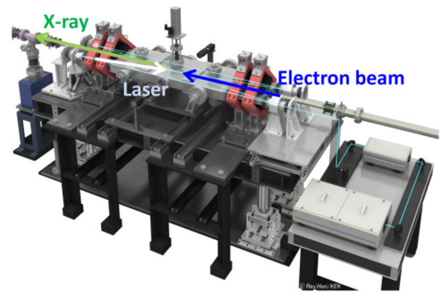

Figure 4: Drawing of the 4-mirror planar optical cavity.

Laser Master System

The length of 4-mirror cavity must be held in the accuracy less than angstrom to keep resonance. It is very difficult to also synchronize to the accelerator simultaneously with this. Therefore the master signal is generated from the signal of laser pulses injected to the cavity. That is to say the accelerator devices such as klystrons synchronize with the cavity and the rf frequency is determined by the length of the cavity. We call this method the laser master system, whose diagram is shown in Fig. 5. By using this method, the 4-mirror cavity should just maintain resonance and the stability has improved very much.

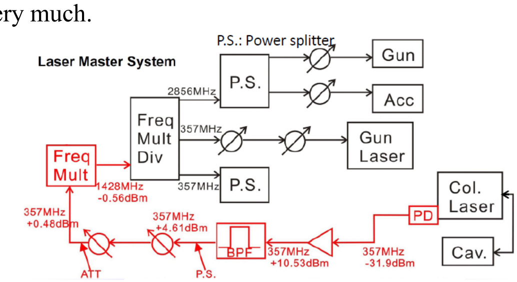

Figure 5: Diagram of the laser master system.

MULTI-BUNCH BEAM GENERATION

We have successfully generated the 300 bunches beam with 26.8 MeV and 380nC total charge now. The 3.6cell rf-gun produces 8.1MeV electron beam and the 12cell booster accelerates up to 26.8MeV.

The beam loading compensation is important issue when accelerating a multi-bunch beam. The loading effect is compensated by injecting the beam in the timing of the transition region when rf power is filled[4]. The compensation optimized by adjusting the timing between an electron beam and a rf pulse. In this upgrade, the accelerating tube is changed into the standing wave type cavity which has with the same Q-value as the rf-gun. This makes the compensation easy because these timings for the compensation become also almost same. Figure 6 shows the measured energy of multi-bunch beam. The energy difference is within 1.2% (peak to peak). The energy spread(rms) of each bunch is also 0.1%.

Figure 7 shows the emittance when changing the solenoid field with the bunch charge of 1.25nC/bunch. The emittance at the solenoid current of 116A is about 5π mm mrad. The beam size at the collision point is also 80μm x 50μm.

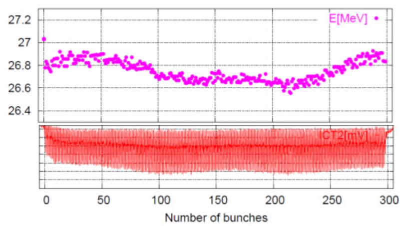

Figure 6: These graphs show the energy of multi-bunch beam and the current transformer waveform.

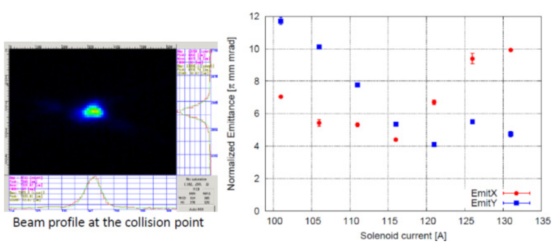

Figure 7: The left picture is the beam profile at the collision point. The right graph shows the result of emittance measurement.

X-RAY IMAGNING TEST

We already start to generate ICS X-rays and to take X-ray images after upgrade. A Micro-Channel Plate (MCP) and a Silicon-On-Insulator (SOI) pixel sensor[5] are used as X-ray detector. The MCP is utilized for measuring the intensity of X-rays. The SOI sensor can take the X-ray image with high spatial resolution because the SOI sensor has very small pixel size of 17μm. The sensor can also obtain the X-ray signal with high signal to noise ratio because the sensor can distinguish an X-ray and a high energy particle by measuring the deposit energy at each pixel or by checking whether the signal is detected along several pixel.

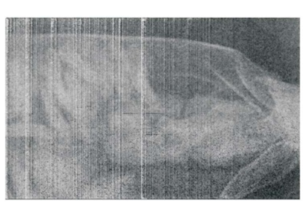

Figure 8: Captured image of chilli pepper by SOI sensor.

We have succeeded to obtain very clear image by the SOI sensor. Figure 8 shows the X-ray image of Chilli pepper[2]. The number of X-rays injected to SOI sensor is 5460 photons/pulse with the energy of 9keV. The number of total band is 5.1×10^5 photons/pulse. The total irradiated number of X-rays to the SOI sensor is 6.7×10^7 photons.

We are trying to increase the intensity of ICS X-ray by increasing the number of electron bunch and the intensity of a laser pulse after X-ray imaging test. Current number of X-rays in total band is 1.4×10^6 photons/train. It is about three times at the time of X-ray imaging test.

SUMMARY AND FUTURE PLAN

We have upgraded the LUCX accelerator and the laser cavity to increase the intensity of X-rays, which increased by about 10 times as compared with upgrade before. The clear image can also be obtained by the SOI pixel sensor.

Table 2 and 3 show the present and target parameters of an electron beam and a laser pulse respectively. The target intensity of X-rays is 1.7×10^7 photons/pulse 10%b.w. at the energy of 15keV in this upgrade. To achieve it, more number of electron bunch and higher energy electron beam is needed as the accelerator side. The target number of electron bunch is 1000bunches/pulse with 30MeV. Therefore we continue the rf processing of 3.6cell rf-gun and 12cell accelerating tube to expand the rf pulse width and to increase rf power. We will try X-ray phase imaging with Talbot-Lau interferometer if we could obtain the higher intensity of X-rays from now.

Table 2: Present and Target Parameters of Electron Beam

	Present	Target
Energy	26.8MeV	30MeV
Intensity	1.25nC/bunch	0.5nC/bunch
Number of bunch	300	1000
Beam size (rms)	33μm x 33μm	80μm x 50μm
Pulse length	15ps	---

Table 3: Present and Target Parameters of Laser

	Present	Target
Wave length	1064nm	---
Pulse energy	0.4mJ/pulse	6mJ/pulse
Beam size (rms)	89μm x 85μm	50μm x 25μm
Pulse length	7ps	---
Collision angle	7.5deg	---

REFERENCES

[1] K. Sakaue et al., AIP Conf. Proc., 1466 272-277 (2012).
[2] K. Sakaue et al., "Development of Laser-Compton X-Ray Source Using Optical Storage Cavity," IPAC'13, Shanghai, May 2013, WEPWA017, p. 2165 (2013); http://www.JACoW.org
[3] T. Aoki et al., "Development of an S-band Multi-cell Accelerating Cavity for RF Gun and Booster Linac," IPAC'11, San Sebastian, September 2011, MOPC020, p. 110 (2011); http://www.JACoW.org
[4] S. Liu et al., Nucl. Instrum. Meth., A584, 1-8 (2008).
[5] Y. Arai et al., Nucl. Instrum. Meth., A636(2011)S31-S36.

ISBN 978-3-95450-138-0