DEVELOPMENT AND UPGRADE PLAN OF AN X-RAY SOURCE BASED ON 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 Laser Compton scattering(LCS) at Laser Undulator Compact X-ray source(LUCX) accelerator in KEK. Our aim is to take a phase contrast image with Talbot interferometer within a few minutes at present. Owing to this, we need the flux of X-ray is 1.7x10^7 photons/pulse with 10% bandwidth. In the accelerator, an electron beam with the energy of 18-24MeV is generated by an S-band normal conducting accelerator. An electron beam collided with a laser pulse stacked in a 4-mirror planar optical cavity and then 6-10 keV X-rays are generated by LCS. Recently, X-ray imaging experiments such as refraction contrast imaging and phase contrast imaging with Talbot interferometer has been conducted. The flux of 9keV X-rays was 3x10^6 photons/sec with total band. Further improvements to realize the design X-ray flux are continued.

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 a synchrotron radiation facility which energy is an order of GeV. They are generally large and expensive. On the other hand, an X-ray source by LCS is possible to realize a similar X-ray energy with a compact accelerator which 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.

In order to develop a compact X-ray source based on LCS, we have constructed the LUCX accelerator at KEK. Here, 6-10 keV X-rays are generated by colliding a multi-bunch electron-beam with the energy of 18-24 MeV with a laser pulse with the wavelength of 1064nm. X-ray imaging experiments including absorption and refraction contrast images has been conducted since 2012. Recently, studies on a phase contrast imaging with Talbot interferometer have been started.

Increasing an energy of electron beam more than 40 MeV will increase the X-ray energy to several tens of keV It will bring a variety of X-ray applications. The possible upgrade plan is discussed.

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LUCX ACCELERATOR

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

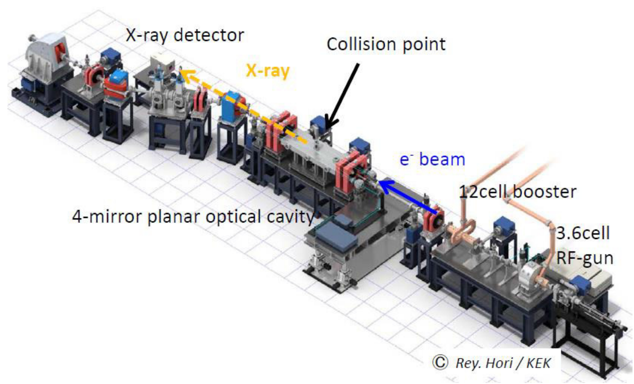

Figure 1: LUCX accelerator.

Two klystrons supply a RF pulse with the width of 4.3μs to the rf-gun and the accelerating tube respectively. The input power into the rf-gun and the accelerating tube is 13MW and 23MW respectively at present.

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

Figure 2 shows a four-mirror planar optical cavity[2] which is a four-mirror bow-tie ring resonator. The cavity consists of two concave mirrors and two flat mirrors. The cavity can enhance the energy of the stored laser pulse by stacking the injected laser pulses which are supplied from a 357MHz mode-locked laser device. The spacing of the laser pulses is 2.8ns. This spacing is the same as that of electron bunches. Therefore, the laser pulses can collide with all bunches of multi-bunch electron beam. Furthermore, the injected pulses are also amplified by two laser amplifiers to boost the energy of the stored laser pulse. This amplification is performed only when an electron

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beam collides a laser pulse in the cavity. Additionally, the stored laser pulse is also focused at the collision point by the concave mirror of the laser cavity.

The parameters of the electron beam and the laser pulse are shown in Table 1 and 2 respectively.

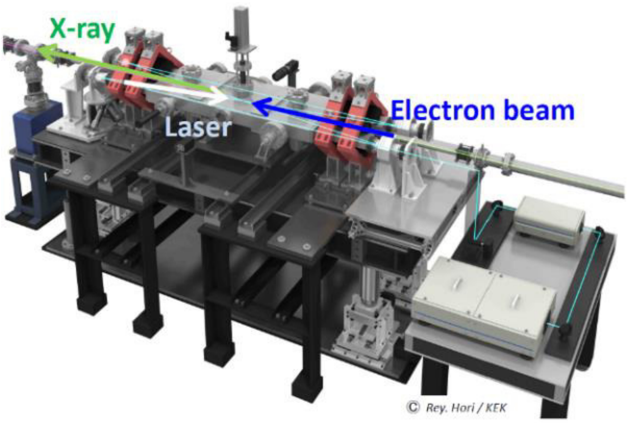

Figure 2: A four-mirror planar optical cavity.

Table 1: Parameters of an Electron beam

	In imaging test	**Design**
Energy	22-24MeV	30MeV
Intensity	0.55nC/bunch	0.5nC/bunch
Number of bunch	700	1000
Beam size (rms)	80µm x 60µm	33µm x 33µm
Pulse length(FWHM)	15ps	15ps

Table 2: Parameters of a Laser Pulse in the Laser Cavity

	In imaging test	**Design**
Wave length	1064nm	1064nm
Intensity	0.84mJ/pulse 300kW	6mJ/pulse 2.1MW
Beam size (rms)	89µm x 85µm	50µm x 25µm
Pulse length(FWHM)	7ps	7ps
Repetition	357MHz	357MHz
Collision angle	7.5deg	7.5deg

X-RAY IMAGING TEST

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. The chamber has two beryllium windows with the thickness of 300µm to pass through X-rays. The MCP is used to measures the intensity of X-rays. The MCP can also be removed from X-ray line by the stepping motor when X-ray image is measured at the downstream of this detector.

X-ray image was taken by a HyPix-3000[3] which is a photon-counting image detector. This detector has the large active area of about 3000mm^2 (77.5x38.5mm^2) with a pixel size of 100µm^2. It was installed at 4.4m and 6.5m from the collision point in case of the test of refraction contrast imaging and phase contrast imaging respectively.

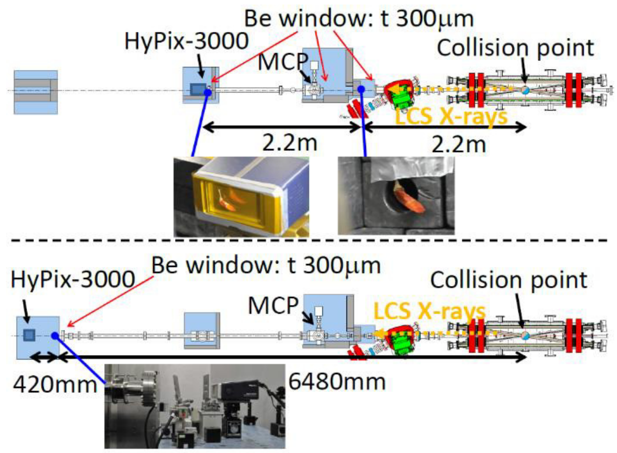

Figure 3: This picture shows the detector position on the X-ray line. The upper side is the setup in a refraction contrast imaging test and the lower side is that in a phase-contrast imaging test.

The parameters of an electron beam and a laser pulse in the imaging tests as shown in Table 1 and 2. The intensity of X-rays was 3x10^6 photons/sec at the collision point and about 0.9 photons/sec/pixel at the image-detector in the imaging tests. The energy of X-rays was 10keV and 9keV in a refraction contrast imaging and a phase contrast imaging respectively. Figure 4 shows the energy distribution calculated by CAIN[4]. The band width of the energy at the detector was about 5%. The source size of the X-rays is the same as the electron beam size at the collision point.

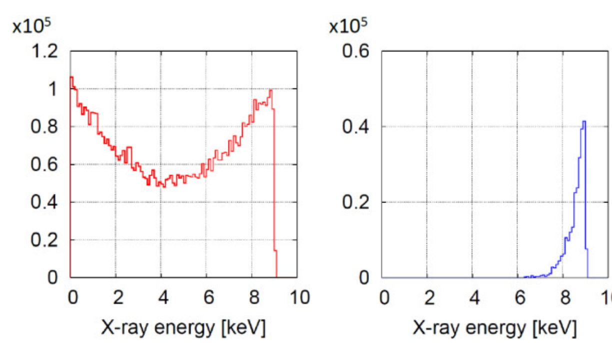

Figure 4: These graphs show the energy distribution of X-ray at the collision point(Left) and at the image detector(Right). The band width of the energy is about 5% at the detector.

We tried to take an absorption and a refraction contrast images of a chili pepper which was placed at just before the image detector and at 2.2 meters upstream of the de-

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tector respectively. The taken images and the line profiles are shown in Fig5. Each exposure time was 300sec. In the line profile of the right image, the contrast at the edge part is clearly emphasized compared with that of the left mage. We could obtain the refraction contrast images.

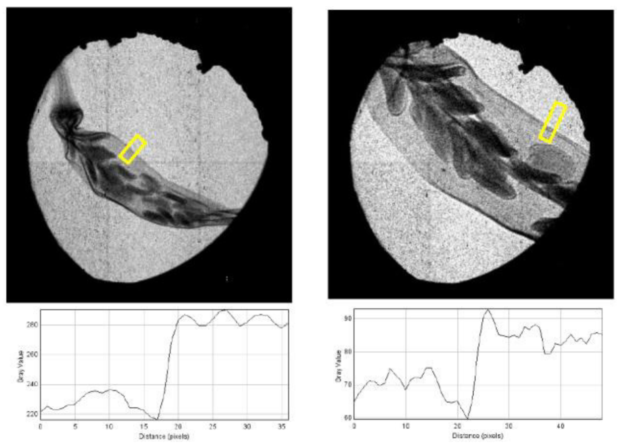

Figure 5: These are taken images. Each sample position of the left and right image is just before the detector and 2.2meters upstream of the detector respectively.

We also tried to take a phase contrast image with Talbot interferometer[5] by using LCS X-rays whose energy is 9keV. The X-rays were guided in the vacuum to avoid the reduction of the intensity by air and then the X-rays were extracted to air through the Be window with the thickness of 300µm at 6.5 meters downstream of the collision point. After that, a sample of an insect, the interferometer and the image detector were installed. We could obtain the phase contrast image. The visibility of the moire fringes was about 33%[6].

However, the exposure time was five hours which are too long for imaging. This long expose time tends to cause influence of the drift of the change of conditions. We need to increase the intensity of LCS X-rays to reduce the exposure time.

UPGRADE PLAN

We have an upgrade plan to increase the beam energy to more than 40MeV by installing an additional accelerating tube shown in Fig.6. The klystron for the existing accelerating tube has enough RF power to drive two accelerating tubes. We expect the energy of LCX X-rays up to 29 keV in the case of an electron beam energy of 40MeV as shown in Fig. 7. The X-rays flux on the detector will be increased because of the X-ray forwarding by a factor of $1/\gamma$. For example, increasing an electron energy from 24MeV to 40MeV results 2.4 times more X-rays on the detector. Moreover, it becomes available to take images of the samples of the materials with higher density because X-rays with the higher energy has a smaller attenuation factor.

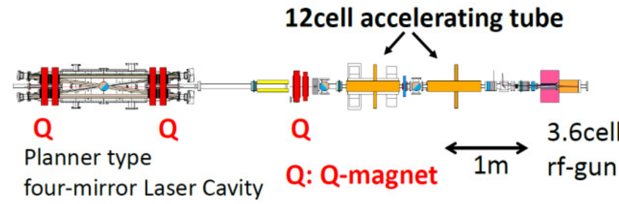

Figure 6: This accelerator part consists of a 3.6cell rf-gun and two 12cell accelerating tubes in the upgrade plan.

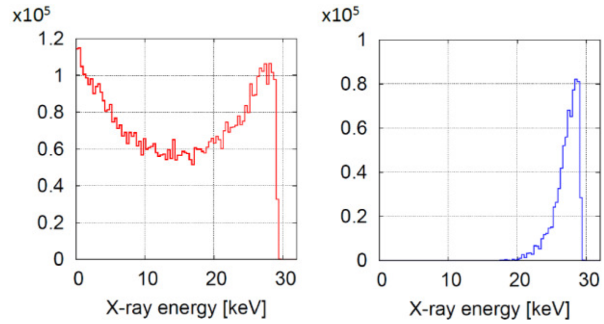

Figure 7: These graphs show the energy distribution of X-rays at the collision point (Left) and at the image detector(Right) when the beam energy is 40MeV

SUMMARY

We have been developed the LCS-Xray source with a compact electron accelerator and an optical cavity. The studies on the X-ray imaging has been successfully conducted; i.e., the refraction contrast image and the phase contrast image with Talbot interferometer. Further improvements to increase the X-ray flux should be continued, especially on the optimization of an electron beam and a laser; the intensity and the focal size at the collision point.

ACKNOWLEDGEMENT

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REFERENCES

[1] M. Fukuda, et.al., Proc. of IPAC'15, Richmond, VA, USA, May 2015, TUPWA065, p. 1576 (2015) ; http://www.JACoW.org

[2] K. Sakaue, et al., Proc. of IPAC'13, Shanghai, May 2013, WEPWA017, p. 2165 (2013); http://www.JACoW.org

[3] Rigaku journal **30** (2), (2014)

[4] CAIN, https://ilc.kek.jp/~yokoya/CAIN/

[5] A Momose, et al., Jpn. J. Appl. Phys. **42** (2003) L866-L868.

[6] M. P. Olbinado, et al., JSR2016, Tokyo, Japan, Jan 2016, 11P080 (2016).