ISBN: 978-3-95450-168-7 doi:10.18429/JACoW-IPAC2015-TUPJE002

DEMONSTRATION OF HIGH-FLUX PHOTON GENERATION FROM AN ERL-BASED LASER COMPTON PHOTON SOURCE

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Abstract

Accelerator and laser technologies required for laser Compton scattering (LCS) photon source based on an energy-recovery linac (ERL) have been developed at the Compact ERL (cERL) facility. A high-flux, energy tunable, and monochromatic photon source such as the ERL-based LCS photon source is necessary for nondestructive assay of nuclear materials. For the demonstration of the ERL-based LCS photon generation, a laser enhancement cavity was installed at the recirculation loop of the cERL. The electron beam energy, the laser wavelength, and the collision angle are 20 MeV, 1064 nm, and 18 deg., respectively. The calculated maximum energy of the LCS photons is about 7 keV. A silicon drift detector (SDD) with active area of 17 mm^2 placed 16.6 m from the collision point was used for observation of the LCS photons. As a result of the measurement, the flux on the detector, central energy, and energy width of the LCS photons were obtained as 1200 /s, 6.91 keV, and 81 eV, respectively.

INTRODUCTION

A high-flux and energy tunable photon generation based on laser Compton scattering (LCS) by an electron beam from an energy-recovery linac (ERL) is a key technology for a nondestructive assay (NDA) of nuclear materials. In order to generate such a photon beam, a small-emittance and high-current electron beam as well as a high-power laser are necessary. The ERL is an optimum apparatus to accelerate a high-quality electron beam [1]. The energy of LCS photons can be selected by changing the electron energy, laser wavelength, or collision angle between the electron and laser beams. Furthermore, the energy width of LCS photons can be narrowed by putting a small-diameter collimator which restricts the scattering angle.

Accelerator and laser technologies required for a high-flux LCS photon generation has been developed at the Compact ERL (cERL) facility. The cERL which is a test accelerator for ERL-based light sources has been constructed by collaborative team of High Energy Accelerator Research Organization (KEK), Japan Atomic Energy Agency (JAEA), other Japanese universities, and institutes [2]. In this paper, we present the first result of the LCS photon generation at the cERL.

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Table 1: Properties of the Electron Beam

Energy [MeV]	20
Bunch charge [pC]	0.36
Bunch length [ps, rms]	2
Spot size [μm, rms]	30
Emittance [mm mrad, rms]	0.4
Repetition Rate [MHz]	162.5

ELECTRON AND LASER BEAM PROPERTIES

The cERL consists of a photo cathode DC electron gun, a normal conducting buncher cavity, a superconducting injector linac, a three-dipole injection merger, a superconducting main linac, and a recirculating beam transport loop. The electron beam with bunch charge of 0.36 pC and bunch length of 3 ps was generated at repetition rate of 162.5 MHz by the photo cathode electron gun with acceleration voltage of 390 kV. The repetition rate of the electron beam pulse in cERL is originally 1300 MHz, but it was changed to 162.5 MHz which is same as the laser repetition for the demonstration of a LCS photon source. The generated beam was accelerated to 2.9 MeV by the injector linac before merging to the recirculation loop. Then, the electron beam was accelerated to 20 MeV by the main linac and was transported to the collision points with the laser beam. The electron beam was focused to rms size of 30 μm and was bunched to rms bunch length of 2 ps at the collision point. After the collision with the laser beam, the electron beam was injected again to the main linac with a deceleration RF phase. The recirculated beam was decelerated and fed back the energy to the superconducting RF cavity. This recovered RF energy was again used to accelerate subsequent electron beam. The properties of the electron beam at the collision point is summarized Table 1.

Since the cross-section of the Compton scattering is small, efficient recycling of laser photons is important to realize a high-flux LCS photon source. This efficient recycling can be achieved by introducing a laser enhancement cavity. The laser enhancement cavity is a high-finesse Fabry-Pérot optical cavity which stores laser pulses injected from an external mode-locked laser. In the LCS photon source, a 4-mirror cavity is employed to achieve high stability and small waist size [3]. As shown in Fig. 1, two sets of 4-mirror cavities are stacked in the same gimbals but are independently adjustable.

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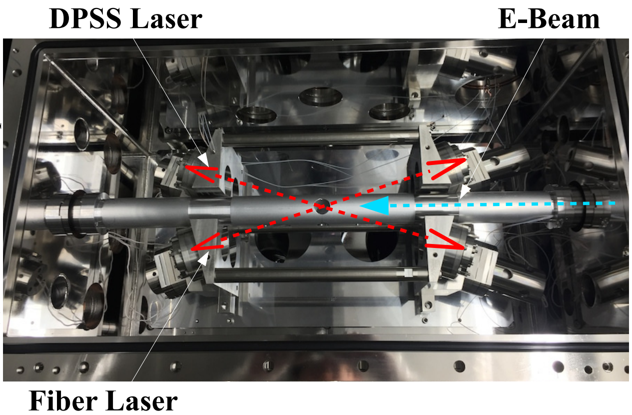

Figure 1: The enhancement cavity, installed on the electron beam line.

For the LCS photon demonstration, two types of lasers were set up and were assigned to two optical cavities to each laser. One is a commercial diode-pumped solid-state (DPSS) laser (Time-Bandwidth Products AG, ARGOS). The DPSS laser has the following features: Maximum average power of 45 W, wavelength of 1064 nm, repetition rate of 162.5 MHz, and pulse length of 5.65 ps. The DPSS laser was installed on a movable optical bench with the enhancement cavity. The position of the laser beam against the electron beam can be adjusted by using the movable optical bench. The other laser is a high-power mode-locked fiber laser which has been developed at Kansai Photon Science Institute, JAEA [4]. The fiber laser consists of a mode-locked oscillator and 4-stage amplifiers; all of them utilize Yb-doped fibers as laser gain media. The fiber laser has the following features: Maximum average power of 100 W, wavelength of 1040 nm, repetition rate of 162.5 MHz, and pulse length of 2 ps. The fiber laser was installed outside the accelerator room, so the laser beam was transported approximately 20 m to the enhancement cavity. We found this long transportation of the laser beam causes pointing instability of the laser beam at the cavity injection and degrades the LCS performance. In the present paper, we show our experimental data with the DPSS laser. The properties of the enhanced laser beam at the collision point is summarized Table 2.

Table 2: Properties of the Enhance Laser Beam

Center wavelength [nm]	1064
Pulse energy [μJ]	64
Pulse length [ps, rms]	5.65
Spot size [μm, rms]	30
Collision angle [deg]	18
Repetition rate [MHz]	162.5

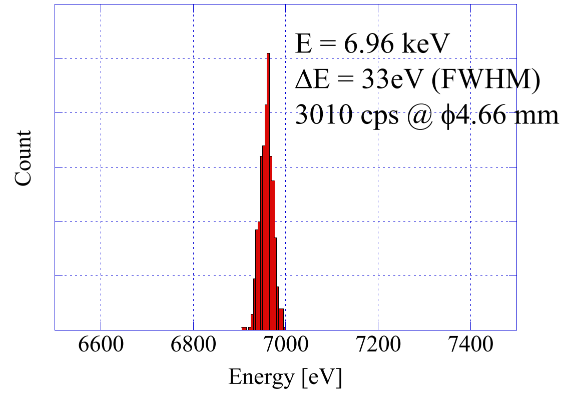

Figure 2: Energy spectrum of the calculated LCS photon at the SDD.

LCS PHOTON GENERATION EXPERIMENT

In the LCS photon generation experiment, the electron beam energy, the laser wavelength and the collision angle were 20 MeV, 1064 nm and 18 deg., respectively. The calculated maximum energy of the LCS photons is about 7 keV. The LCS photon beam was transported to an experimental hatch through a vacuum beam line. A silicon drift detector (SDD) with active area of 17 mm^2 used for the LCS photon observation was placed 16.6 m from the collision point. The beryllium windows were installed at both ends of the beam line, *i.e.*, the accelerator side and the experimental hatch side. The distance of the experimental hatch side Be-window and the SDD was 12 cm in the air. The transparency of the Be-windows and the 12-cm air is about 64.8 %. The LCS photon flux at the SDD was calculated to be 3.01×10^3 /s from CAIN [5] simulation. As shown in Fig. 2, the calculated central energy of the LCS photons is 6.96 keV and the FWHM width of 33 eV.

The position of the laser and the electron beam were matched by using the screen monitor at the collision point. The collision timing was searched by observing the photon by SDD in an asynchronous state of the laser and the electron beam (see Fig. 3). From the result of this asynchronous run, we can find the laser phase to obtain right collision with the electron bunches. We measured LCS X-ray performance after the laser phase was locked on the right timing. Figure 4 shows an measured energy spectrum of the LCS photons by the SDD. The count rate, central energy, and energy width of the LCS photons were obtained as 1200 /s, 6.91 keV, and 173 eV in FWHM. The photon flux is about 40 % of the expectation. The energy width of the SDD was measured to be 153 eV in FWHM for 5.9-keV X-rays from ^{55}Fe. Assuming quadratic nature for convolution of width, the energy width of the LCS photon beam is estimated to be 81 eV.

In Fig. 4, we can see that background noise originating from Bremsstrahlung of 20-MeV electrons, which appears energies above the X-ray peak, is very small. X-ray signals

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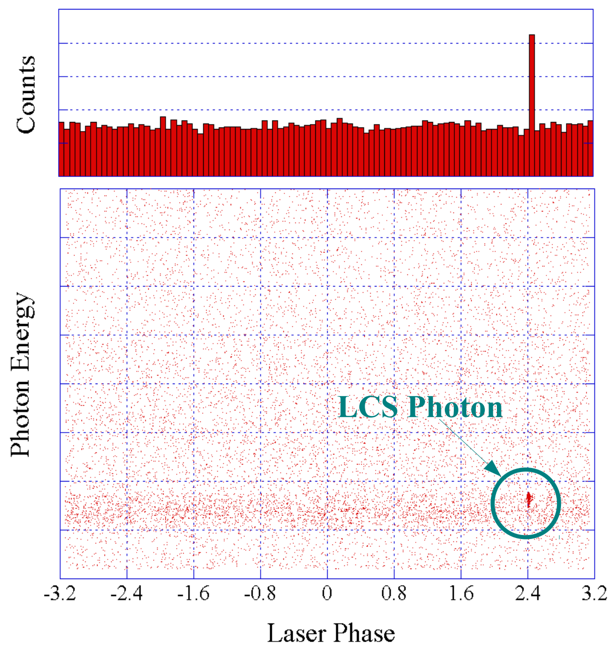

Figure 3: Detected photon plot in an asynchronous state of the laser and the electron beam.

below the peak energy are attributed to imperfect energy deposition of LCS photons in the detector such as Compton continuum and escape peaks. The good signal-to-noise ratio of the LCS X-ray obtained at the cERL will be advantage in various X-ray applications.

We have conducted experiments of X-ray imaging [6] and X-ray florescence (XRF) [7] as demonstration of LCS X-ray beam applications. See the references for detail results.

The total LCS photon flux at the collision point corresponding to the X-ray spectrum in Fig.4 is estimated as 4.1×10^7 /s with the average beam current of 57.7 μA. We plan to increase the electron beam current of cERL from the present value, 100 μA, to the design value, 10 mA, in near future with a better management of unexpected electron beam losses. In parallel with the electron beam upgrade, we continue to improve the enhancement cavity performance for delivering laser photons with the higher pulse energy to the collision point. These efforts towards the increase of LCS photon flux contribute to expansion of application research utilizing the LCS X-rays at the cERL.

SUMMARY

We have generated an X-ray beam with an energy of 6.91 keV and an energy-width of 81 eV from laser Compton scattering in the cERL. This is the first experimental demonstration of LCS photon generation with an energy-recovery linac and a laser enhancement cavity. The photon flux at the collision point is estimated as 4.1×10^7 /s with the average beam current of 57.7 μA. The technologies of LCS photon generation established here can be applied to future high-flux gamma-ray [8] and compact X-ray [9] sources.

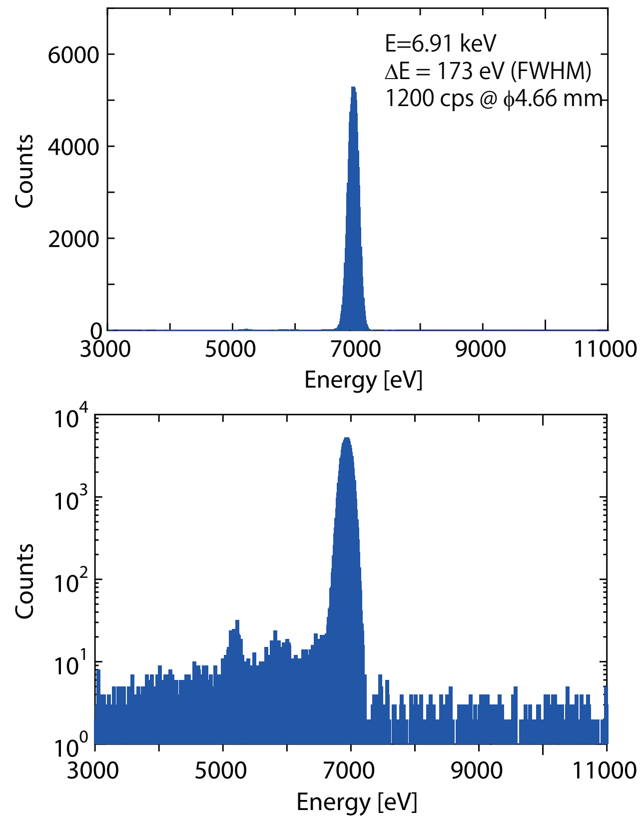

Figure 4: Energy spectrum of the observed LCS photon at the SDD with a linear scale (top) and a logarithmic scale (bottom).

ACKNOWLEDGMENT

This study is supported in part by a Government (MEXT) Subsidy for Strengthening Nuclear Security and by Photon and Quantum Basic Research Coordinated Development Program of MEXT, Japan.

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