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CONSTRUCTION OF A LASER COMPTON SCATTERED PHOTON SOURCE AT cERL

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Abstract

A high intensity γ-ray source from the laser Compton scattering (LCS) by an electron beam in an energy-recovery linac (ERL) is a key technology for a nondestructive assay system to identify nuclear materials. In order to demonstrate accelerator and laser technologies required for a LCS photon generation, a LCS photon source is under construction at the Compact ERL (cERL). The LCS photon source consists of a mode-locked fiber laser and a laser enhancement cavity. A beamline and an experimental hatch are also under construction. The commissioning of the LCS photon source will be started in February 2015 and LCS photon generation is scheduled in March 2015.

INTRODUCTION

A nondestructive assay system to identify nuclear materials by means of nuclear resonance fluorescence is under development at Japan Atomic Energy Agency (JAEA) for the nuclear nonproliferation and security. Quasi-monochromatic γ-rays generated by laser Compton scattering (LCS) based on energy-recovery linac (ERL) accelerator and laser technologies are utilized for the nondestructive assay system. In a LCS γ-ray source, γ-ray energies can be selected by changing the electron energy, laser wavelength or collision angle. Furthermore, the energy width of γ-rays can be sharpened by putting a small-diameter collimator to restrict the scattering angle. The LCS γ-ray source is distinguished from other conventional γ-ray sources in its energy tunability, narrow energy width and small divergence.

In order to generate high-flux and high-brightness γ-rays by LCS, a small-emittance and high-current electron beam and a high-power laser are necessary. An ERL is the optimum apparatus to accelerate electron beams with small-emittance and high-average current [1]. The Compact ERL (cERL) [2], a test accelerator for ERL-based light sources, has been constructed by collaborative team of High Energy Accelerator Research Organization (KEK), JAEA and other Japanese universities and institute. In order to demonstrate the performance of the accelerator combining with a high-power mode-locked laser system for generating γ-rays, an LCS photon source and the peripheral equipment are under construction at the cERL. In this paper, we present overview of the cERL and design of the LCS photon source, beam line and other experimental facilities.

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OVERVIEW OF THE cERL

The performance of ERL, e.g., electron beam current and emittance, is dominated by its electron source and accelerating structure. The photocathode electron gun and superconducting accelerator (SCA) are key technologies to accelerate a small emittance and high-current electron beam. The collaboration team has developed a photocathode electron gun and SCA optimized for ERLs. The cERL has been constructed to demonstrate these key technologies in beam operations. Design parameters of the cERL are listed in Table 1. The layout of the cERL is shown in Fig. 1. Since the design energy of electron beams at the cERL is 35 MeV, LCS photons will have an energy of 22 keV. However, the LCS photon source at the cERL is regarded as a demonstration of high-flux LCS γ-ray source for the nondestructive assay system to identify nuclear species. Increasing the LCS photon energy is simply achievable by adding more SCAs for higher electron energy. A space for additional SCAs and second recirculation loop is reserved for a future energy upgrade of the cERL [3] as shown in Fig. 1. After the full upgrade of the cERL, an electron beam of 245 MeV will be available and will produce 1 MeV γ-rays.

Table 1: Design Parameters of cERL

Beam energy [MeV]	35 (initial goal) 245 (upgradable in future)
Injection energy [MeV]	5
Beam current [mA]	10 (initial goal) 100 (future goal)
Normalized emittance [mm mrad, rms]	1 (initial goal) 0.1 (at low current)
RF Frequency [MHz]	1300
Bunch length [ps, rms]	1–3 (usual) ≤ 0.1 (under compression)

A DC electron gun equipped with a semiconductor photocathode has been designed and fabricated at JAEA to generate small-emittance and high-current electron beams. The beam generation of the electron gun has been successfully demonstrated at the world-highest voltage, 500 kV, and a high-average current up to 10 mA [4]. In case of usual high-voltage DC photocathode guns, the operational voltage has been restricted to 350 kV or lower owing to the field emission problem, which causes electrical breakdown or punch-through on the ceramic insulator. In the JAEA gun, a segmented insulator with guard-rings has been employed to keep the insulator safe from the field emission

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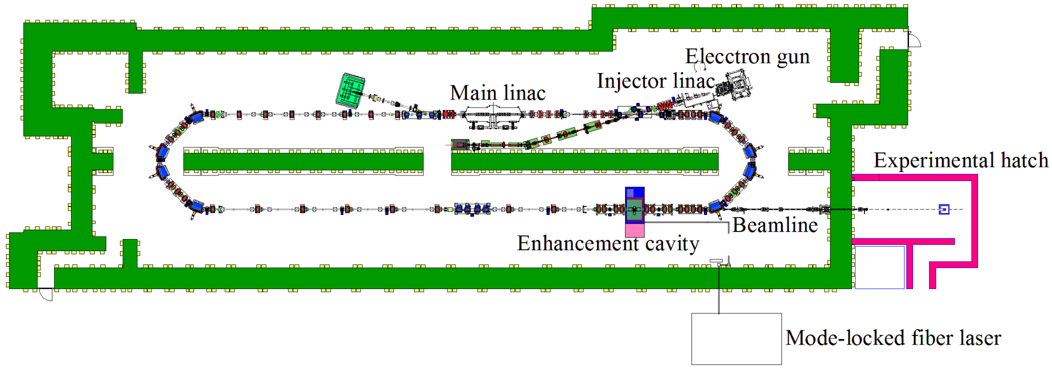

Figure 1: Layout of the cERL.

generated from a central stem electrode to solve the field emission problem [5]. After the successful demonstration of 500-keV beam generation, the gun was shipped to KEK, and was installed at the cERL. The beam operation of the cERL was started from April 2013. At present, the gun provides an electron beam for daily operation of cERL.

Two types of SCAs for the cERL have been developed at KEK, one for the injector and the other for the main linac [6]. The operation frequency and temperature of the SCAs are 1300 MHz and 2 K, respectively. The injector is three 2-cell cavities housed in a cryomodule. In the injector, a high-current electron beam is accelerated without energy recovery. Therefore, a twin-coupler system was employed to reduce the input power per coupler. The main linac is two 9-cell cavities housed in a cryomodule. In the main linac, suppression of higher-order mode (HOM) is a main issue to avoid the beam-breakup instability. A beam-pipe-type HOM absorber was employed to achieve strong HOM damping. The HOM absorbers are placed at both the ends of the 9-cell cavity and inside the cryomodule, at temperature of 80 K. The electron beam generated in the photocathode gun is accelerated to 5 MeV by the injector. The beam is further accelerated to 35 MeV by the main linac and radiate the γ-rays at the LCS section. The beam injected again to the main linac through the recirculation loop is deccelated to 5 MeV, and is dumped. The commissioning of the cERL was started from December 2013. The energy recovery operation at a recirculation energy of 20 MeV was successfully achieved in February 2014.

DESIGN OF THE LCS PHOTON SOURCE AND THE PERIPHERAL EQUIPMENT

In order to demonstrate high-flux and high-brightness LCS photon beam generation at the cERL, a laser enhancement cavity will be installed at the recirculation loop of the cERL. The LCS photon beam is transported to an experimental hatch through a vacuum beam line for evaluation of the LCS photon source. Figure 1 shows a floor layout of the LCS photon source and other experimental facilities at the cERL. The commissioning of the LCS photon source

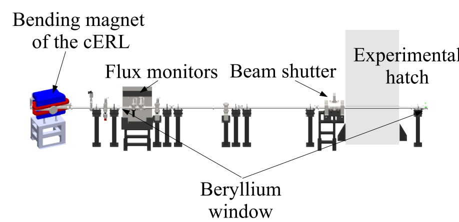

Figure 2: Schematic drawing of the beamline.

Table 2: Design Parameters of the Enhancement Cavity

Frequency [MHz]	162.5
Enhancement factor	2550
Collision angle [deg]	18
Spot size [μm, rms]	20 (hor.), 30 (vert.)

will be started in February 2015 and LCS photon generation is scheduled in March 2015 . The beam line consists of two beryllium vacuum windows, a beam shutter, two flux monitors as shown in Fig. 2. The beryllium windows are installed at both ends of beam line, the accelerator side and the experimental hatch side. The beam shutter is 20 cm in thickness and is made of lead. A thin scintillator and a silicon drift detector are located just after the first beryllium window as flux monitors.

Since the cross-section of the Compton scattering is small, efficient recycling of laser photons is important to realize a high-flux and high-brightness γ-ray source. This efficient recycling of laser photons is achieved by introducing a laser enhancement cavity. The laser enhancement cavity is a high-finesse Fabry-Perot 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 [7]. As shown in Fig. 3, two sets of 4-mirror cavities are stacked in the same gimbals. Design parameters of the enhancement cavity are listed in Table 2.

A high-power mode-locked fiber laser for the LCS photon source is under development at Kansai Photon Science

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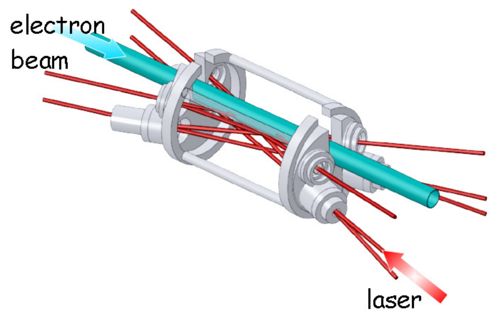

Figure 3: Schematic drawing of the enhancement cavity.

Institute, JAEA [8]. The laser consists of a mode-locked oscillator and 4-stage amplifiers; all of them utilize Yb-doped fibers as laser gain media. Since the LCS γ-ray bandwidth is affected by laser bandwidth, a high-power laser with narrow-bandwidth has been developed. The laser system is, thus, equipped with two pulse stretchers and one compressor to avoid nonlinear spectral broadening during the amplification. Bandpass filters are also inserted between amplification stages. The laser has been completed and ready for shipping to the cERL. Design parameters of the mode-locked fiber laser are listed in Table 3.

Table 3: Design Parameters of the Mode-locked Fber Laser

Average power [W]	~ 100
Center wavelength [nm]	1030
Band width [nm, FWHM]	1.4
Pulse duration [ps]	~ 2
Repetition rate [MHz]	162.5

In the first demonstration of the LCS photon source scheduled in March 2015, typical operation mode of the cERL will be a macropulse width of 1 ms and a bunch charge of 0.77 pC. The recirculation energy will be 20 MeV to avoid field emission from the SCA. The parameters of the LCS photon source corresponding to the cERL parameters are summarized in Table 4. The divergence of LCS photons is restricted by the diameter of beryllium window, 50 mm, at the experimental hatch, 16.6 m from the LCS source.

The LCS photon flux at the experimental hatch was estimated to be 3.5×10^7 ph/s at macropulse average from CAIN [9] simulation. As shown in Fig. 4, the energy spectrum of the LCS photons is the center energy of 7.18 keV and the FWHM spectrum width of 0.043 keV.

SUMMARY

A quasi-monochromatic LCS photon source based on an ERL is under development for a future nondestructive assay system of nuclear materials. In order to demonstrate accelerator and laser performance required for the LCS source, we are constructing an LCS photon source, beam line and other experimental facilities at the cERL, a test accelerator

Table 4: Typical Parameters of the LCS Photon Source

Parameters of the electron beam	
Energy [MeV]	20
Bunch charge [pC]	0.77
Bunch length [ps, rms]	3
Spot size [μm, rms]	50
Emittance [mm mrad]	0.3
Parameters of the laser	
Wavelength [nm]	1030
Energy per pulse [mJ]	1.5
Pulse duration [ps, rms]	2
Collision angle [deg]	18
Spot size [μm, rms]	50

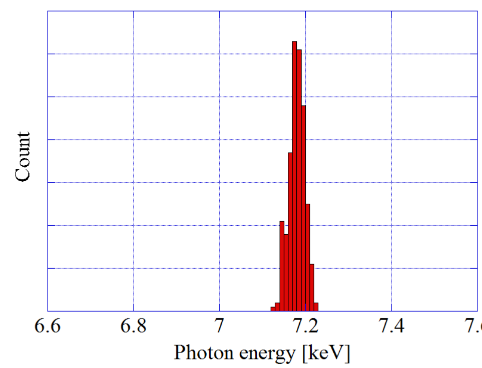

Figure 4: Energy spectrum of the LCS photon beam at the experimental hatch.

for ERL-based light sources. The energy recovery operation at the cERL was achieved in February 2014 and further studies to improve the beam quality are in progress. The commissioning of the LCS photon source will be started in February 2015 and LCS photon generation is scheduled in March 2015. In the first demonstration of the LCS photon source, the LCS photon flux at the experimental hatch will be 3.5×10^7 ph/s at macropulse average under the typical parameters.

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