

DEVELOPMENT OF A HIGH AVERAGE POWER LASER FOR HIGH BRIGHTNESS X-RAY SOURCE AND IMAGING AT cERL

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Abstract

High brightness X-rays via laser-Compton scattering (LCS) of laser photons stored in an optical cavity by a relativistic electron beam is useful for many scientific and industrial applications such as X-ray imaging. The construction of compact Energy Recovery Linac (cERL) is now in progress at KEK to generate low-emittance and high-current electron beams. In order to demonstrate the generation of high brightness LCS X-rays, it is necessary to develop a high average power injection laser and an optical four-mirror ring cavity with two concave mirrors which is used to produce a small spot laser beam inside the cavity. In this presentation, we will show the result of the development of the high average laser system, the LCS X-rays generation, and the X-ray imaging.

INTRODUCTION

There has been a growing interest in the laser-Compton scattering (LCS) light source. The LCS and a high average power laser with an optical cavity enables generation of monochromatic, bright and tuneable X-rays. Such a photon source is expected to bring breakthrough in fundamental researches [1], medical [2] and industrial applications [3].

The development of the Compact ERL (cERL) is ongoing at KEK to produce low emittance and high-current recirculating electron beams [4]. By combining advanced laser technology with the cERL, a high brightness LCS X-ray beam can be generated. In this paper, we will show the detailed properties of the high average laser used for the LCS X-ray generation at cERL.

We will also show the results of the measurement of the LCS X-rays and the X-ray imaging.

PERFORMANCE OF THE SEED LASER SYSTEM AND THE OPTICAL CAVITY

In our experiments, we employ a commercial passively mode-locked diode pumped solid state laser system (ARGOS, Time Bandwidth Products (JDSU)). The oscillator operates at a repetition rate of $f_{rep} = 162.5$ MHz which has an integer relation with the fundamental RF of the cERL. This laser system delivers an average power of 45 W and pulse duration of 10 ps. The laser beam ejected from the laser system is passed through a mode matching telescope in order to match the laser beam to the cavity mode.

We employ a four-mirror cavity with two concave mirrors to produce a small spot laser beam inside a cavity. Since the LCS X-rays are generated by collision of laser photons and relativistic electrons, the laser beam is required to be well focused at the collision point where the spot size (rms) of the cERL electron beam at the experiment is about 13 - 130 μm (horizontal) and 20 - 25 μm (vertical).

The optical setup of our cavity locking laser system is shown in Fig. 1 (a). The optical cavity consists of two flat mirrors (M1 and M2) and two concave mirrors (M3 and M4). The radius of curvature of the concave mirrors which are manufactured by LMA (Laboratoire des Matériaux Avancés) is 420 mm and the reflectivity is about 99.999 %. The reflectivity of the flat mirror (M2) is 99.99 % and the input coupler mirror (M1) is 99.9 %.

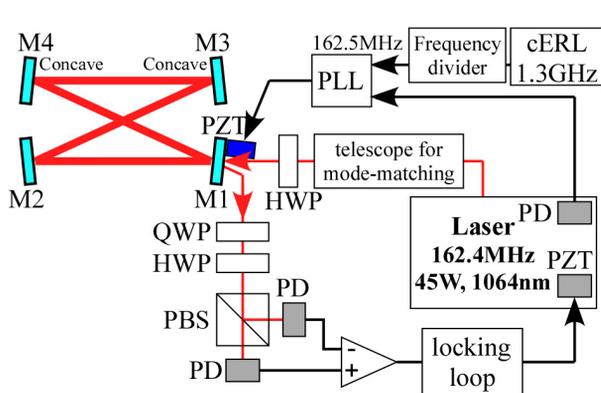


Figure 1: Schematic diagram of the optical cavity and a cavity locking loop configuration and the picture of the laser system and the optical cavity on the movable table in the cERL accelerator room.

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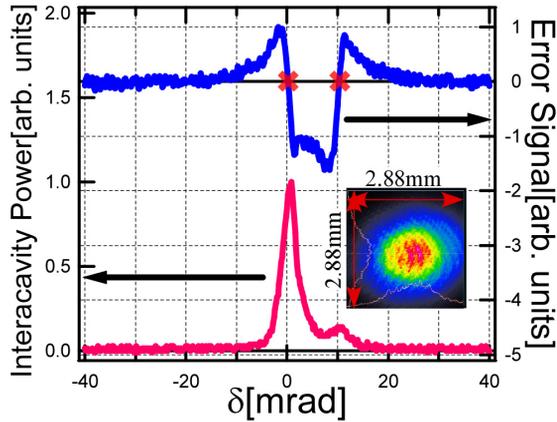


Figure 2: Observation of the intracavity power (Red) and error signal (Blue). The lock-points (Zero-crossing point) are denoted by crosses. Inset represents the spatial profile of the enhanced beam.

These flat mirrors are manufactured by REO (Research Electro-Optics, Inc.). The enhancement factor P of the cavity is calculated to be 3200. Therefore, the finesse F is 5600. The enhancement factor P is defined as $P = P_{circ}/P_{in}$, where P_{circ} and P_{in} denote the circling intracavity power and the seeding laser power, respectively. The circling intracavity power P_{circ} is determined by measuring the power leaking from a concave mirror (M3, LMA) and divide it by the mirror transmission of 7.5 ppm. From the leaking power measurement, when the P_{in} was 24 W, a circulating power $P_{circ} = 10.4$ kW was obtained. The enhancement factor can be further improved by suppressing the electrical noise of the cavity locking loop and the laser fluctuation caused by the mechanical vibration of the optical table.

The optical cavity lock is realized with a Hansch-Couillaud method [5], which utilizes polarization by monitoring changes in the polarization of the light field reflected from the cavity. In contrast to the original scheme, where a Brewster plate or a polarizer inside the cavity is needed, in our case the necessary polarization discrimination is given by the nonorthogonal incidence of the optical beam on the cavity mirrors. Figure 2 shows the measured intracavity power through the cavity mirror and error signal for linear scan of the cavity length. The polarization of the two adjacent peaks of the resonance condition is at right angle to each other. Inset of Fig. 2 shows the transmitted laser beam profile measured behind the cavity mirror M2. We obtained the beam size of $\sigma_x = 0.59$ mm and $\sigma_y = 0.50$ mm. From this measurement together with a calculation by using the ABCD matrix, the waist sizes at the laser-electron interaction point are estimated as $\sigma_x = \sigma_y = 30$ μ m.

LCS X-RAY GENERATION AND X-RAY IMAGING EXPERIMENT

The LCS X-ray generation and imaging experiment were performed at the cERL located at KEK. The

Table 1: Parameters of Electron and Laser Beams

Intracavity Laser beam	
Center wavelength [nm]	1064
Pulse energy [μ m]	64
(Average power [kW])	10.4
Pulse duration [ps, rms]	5.65
Spot size [μ m,rms]	30
Collision angle [deg.]	18
Repetition rate [MHz]	162.5
Electron beam	
Energy [Mev]	20
Bunch charge [pC]	0.36
Bunch length [ps, rms]	2
Spot size [μ m, rms]	30
Emittance [mm mrad, rms]	0.4
Repetition Rate [MHz]	162.5

parameters of laser and electron beam at the collision point are shown in Table 1. Figure 3 shows the layout of the LCS X-ray experimental setup, which consists of the cERL beamline, the LCS X-ray beamline with two beryllium windows and X-ray detector in the experimental hatch. The beryllium windows are installed at both ends of beamline, accelerator side (thickness of 250 μ m) and the experimental hatch side (thickness of 300 μ m).

Around 7 keV X-ray was generated by collision of 1064 nm laser photons and 20 MeV electrons at an angle of 18 deg. In this experiment, we used two types of X-ray detectors. One is a silicon drift detector (XR-100SDD, AMPTEK Inc.) for an X-ray intensity evaluation, the other is a 2D photo counting X-ray detector (HyPix-3000, Rigaku) for imaging experiments.

The LCS X-ray intensity evaluation was firstly performed using the silicon drift detector. The detector was installed in front of the beryllium window in the experimental hatch. Before the measurement, we roughly adjusted spatial overlap between the laser and electron beam by changing the laser spot position. The laser system and the optical cavity are mounted on a movable table. Figure 4 (a) shows the observed LCS X-ray intensity as a function of the vertical position of the laser

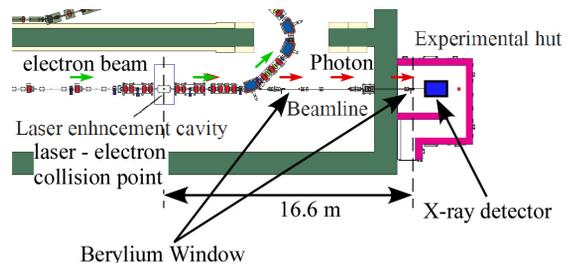


Figure 3: Schematic view of the optical cavity and the beamline for the LCS X-ray source.

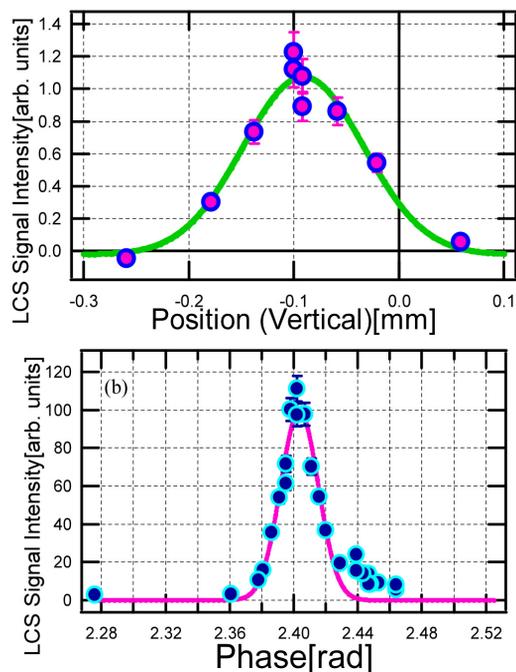


Figure 4 (a): LCS X-ray intensity as a function of the vertical position of the laser beam. (b): LCS X-ray intensity as a function of the collision timing to laser beam and electron beam.

beam. The LCS X-ray intensity is normalized by the stored laser power inside the cavity. The width of vertical position scan is $57.6 \mu\text{m}$ in σ . This value corresponds to the convolution of the laser and electron size of the vertical position scan. Then the vertical position of the laser beam was set at the maximum X-ray intensity. After this position scan, we performed the longitudinal position (timing) scan. Figure 4 (b) shows the observed LCS X-ray intensity as a function of the collision timing between the laser and electron beam. The width of distribution is 0.0166 rad which corresponds to 11.5 ps . This value seems to be the timing jitter rather than the convolution of the longitudinal length laser and electron beam. The laser timing was locked to the phase of the maximum intensity by using a PLL method. From the measured SDD spectrum, the central energy of 6.91 keV , the FWHM spectrum width of 0.173 keV and detector count rate of 1200 cps was obtained within a detector area, $\phi 4.66 \text{ mm}$. The measured spectrum width reflects the detector resolution, 0.162 keV at 5.89 keV . We will make further detail measurements with crystal monochromator in near future for characterizing spectral purity of the LCS X-rays. The LCS photon flux at the collision point is estimated to be $4.3 \times 10^7 \text{ photons/sec}$ from CAIN/EGS simulation with the above measurement results [6].

The LCS X-ray imaging was carried out by the setup shown in Fig. 5 (a). The resulting X-ray image is shown in Fig. 5 (b). This image was obtained by 10 minutes accumulation to achieve the enough statistics. Due to the small source size of LCS X-rays, it is possible to perform refraction contrast imaging [7] which allows enhancement of the edge of X-ray imaging. And we set the detector at a

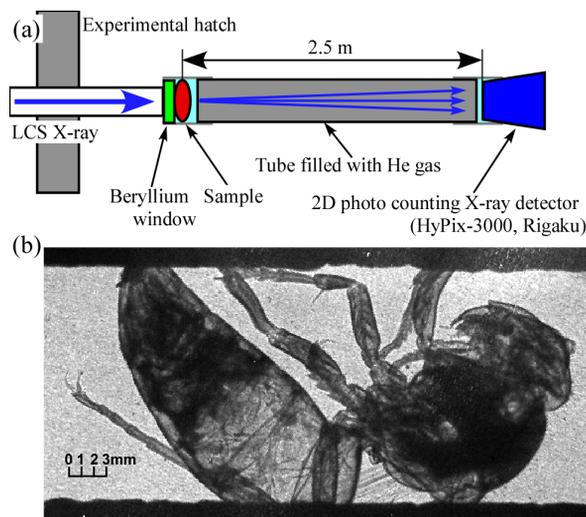


Figure 5 (a): The schematic of LCS X-ray imaging experimental setup. (b): LCS X-ray imaging of hornet.

distance of 2.5 m from the specimen. Since the transmittance of the 7-keV X-ray in the air is low, the tube filled with He gas was placed between the beryllium window and the detector. The transmittance of the 7-keV X-rays in He is almost 100% . Therefore, it was possible to obtain the high contrast X-ray image shown in Fig. 5 (b).

CONCLUSION

We have demonstrated the generation of LCS X-ray at cERL in KEK. We have developed a high average power laser used for the generation of the LCS X-rays. The X-ray energy was measured to be 6.91 keV by a silicon drift detector, while the photon flux at the collision point was estimated to be $4.3 \times 10^7 \text{ photons/sec}$. We performed the high contrast X-ray imaging of a hornet by using a 2D photo counting X-ray detector. From the obtained imaging, we confirmed that LCS X-rays from a small source size are useful for phase-contrast X-ray imaging. In the present photon flux, it takes 10 minutes to obtain one image. We plan to increase the photon flux by improving the enhancement factor of the optical cavity to take an image in a short time.

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