DEVELOPMENT OF AN OPTICAL CAVITY FOR LCS SOURCES AT THE COMPACT ERL

T. Akagi*, S. Araki, Y. Honda, A. Kosuge, N. Terunuma, J. Urakawa, KEK, Ibaraki, Japan
R. Hajima, M. Mori, R. Nagai, T. Shizuma, QST, Tokai, Japan

Abstract

High-energy photons from the laser Compton scattering (LCS) sources are expected to be applied in various fields in a wide range photon energies from keV to GeV. High-flux and narrow-bandwidth LCS photon beam is realized in an energy recovery linac (ERL). An electron beam of high-average current and small-emittance collides with accumulating laser pulses in an enhancement cavity for generating high-flux LCS photon beam. We have developed the high-finesse bow-tie ring cavity for the LCS experiment at the Compact ERL (cERL) in KEK. In this presentation, we will report the detail of the optical cavity.

INTRODUCTION

The photon source based on laser Compton scattering (LCS) can generate high-energy photons with relatively low-energy electrons in comparison with the synchrotron. Therefore LCS photon sources are suitable for developing the compact light sources. The LCS sources has several features such as narrow bandwidth, energy tunability, small source size, and polarization control.

Photon flux and energy bandwidth are important parameters of LCS sources. To realize a high-flux and a narrow bandwidth photon source, a high-average-current and a small emittance electron beam is essential. Energy recovery linacs (ERLs) can produce a such electron beam. On the laser system, a high-power and tightly focused laser pulse with a repetition rate that matches the electron beam is needed. We have developed an optical cavity for the LCS interaction point (IP), in which laser pulses from a mode-locked laser are stacked and enhanced. We have been developing the ERL-based LCS sources with a laser enhancement cavity at a test accelerator of ERL at KEK, the Compact ERL (cERL). We have generated 7-keV LCS X-ray in the cERL [1]. We will describe progress of development of the optical cavity.

ACCELERATOR

The cERL is a test facility constructed for the development of accelerator components and technologies necessary for future ERL-based light source. The cERL has been designed to achieve a small-emittance electron beam with a high average current.

The cERL consists of an injector, a superconducting linac, and a recirculation loop. A interaction point (IP) for the LCS is located in the straight section of the circulation loop. In the LCS experiment, the cERL is operated at a recirculation energy of 20 MeV and a pulse repetition rate of 162.5 MHz. Recently, we have achieved to circulate 1 mA [2].

In this experiment, the beam current was limited to 1 mA, the value approved by the regulatory authority at the time. The parameters of the electron beam for the LCS experiment are listed in Table 1.

Table 1: Parameters of the Electron Beam for the LCS Experiment

Energy [MeV]	20
Bunch charge [pC]	5.5
Bunch length [ps, rms]	2
Spot size (σ_x/σ_y) [μm]	22/32
Emittance ($\varepsilon_{nx}/\varepsilon_{ny}$) [mm·mrad]	2.52/1.25
Repetition rate [MHz]	162.5

OPTICAL CAVITY

In order to produce a high-flux LCS X-ray, it is necessary to achieve a high finesse and a small laser waist size simultaneously. A 2-mirror Fabry-Perot cavity is unstable for small waist size. Therefore, we developed a 4-mirror ring cavity which consists of two plane mirrors and two concave mirrors. It is more tolerant of misalignment of mirrors than a 2-mirror cavity. A detail description of the design of the optical cavity can be found in [3]. The design parameters of the optical cavity are summarized in Table 2.

We used a commercial laser system consisting of a mode-locked oscillator and an amplifier (ARGOS, TimeBandwidth-Product) with wavelength, repetition rate, average power, pulse width (FWHM) were, 1064 nm, 162.5 MHz, 45 W and 10 ps, respectively.

Table 2: Design Parameters of the Optical Cavity

Repetition rate [MHz]	162.5
Finesse	5600
Spot size at the IP (σ_x/σ_y) [μm]	20/30
Input angle of mirrors [degree]	4.3
Diameter of mirrors [mm]	25.4
Curvature radius of mirrors [mm]	420

A photograph of the optical cavity is shown in Fig. 1. Two sets of 4-mirror cavities having a common focal point are combined symmetrically in the same structure. Only one set was used for the LCS experiment at present. Two sets cavities have been designed to produce two different polarization X-ray beams at the same time.

* akagit@post.kek.jp

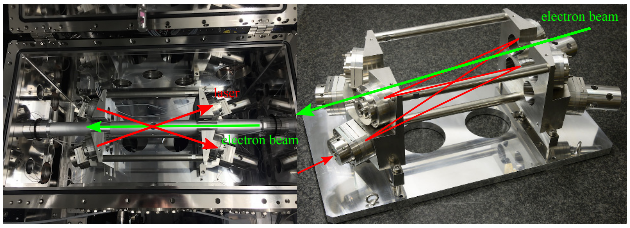

Figure 1: The optical cavity structure.

Feedback System

The error signal to stabilize the optical cavity was produced by Pound-Drever-Hall (PDH) method [4]. It is the well-known technique for locking laser frequency to the optical cavity. In our case, electro-optic modulator (EOM) cannot be used in high power such as 45 W laser. Therefore, we applied phase modulation to a part of incident laser beam and the light was injected to the optical cavity in a direction opposite to main laser pulse. The optical system is shown in Fig. 2.

We need two types feedback control. One is to accumulate laser pulses in the optical cavity, called cavity locking. The other is to synchronize the laser pulse to the electron beam, called phase locking. The block diagram of the feedback system is shown in Fig. 3. The cavity locking was performed with the piezo actuator inside the oscillator. The phase locking was performed with the piezo actuator of the cavity. Since the cavity locking required a faster control for keeping a narrow resonance condition, the oscillator piezo was chosen for it. We had measured the frequency characteristics of our mode-locked laser. In this measurement, a sinusoidal signal applied to piezo actuator from a Frequency Response Analyzer (FRA). Then, the gain and relative phase with respect to the sinusoidal wave was measured with the FRA. The frequency response of the piezo actuator inside laser oscillator is shown in Fig. 4. The results indicates that feedback bandwidth of cavity locking is limited to less than 30 kHz. Widening the feedback bandwidth is essential for improving cavity locking stability. For example, a feedback response can be faster than 100 kHz by using an acousto-optic modulator (AOM) frequency shifter in the transport line [5].

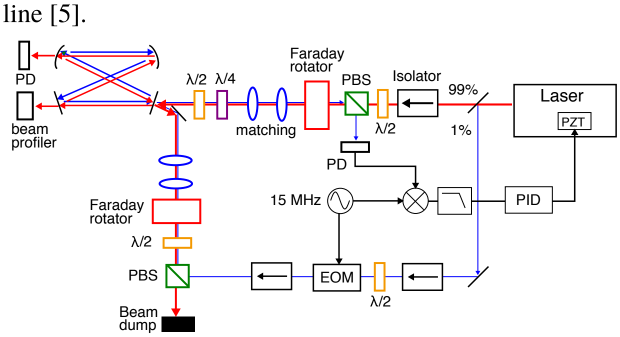

Figure 2: Setup of the optical cavity system.

CAVITY PERFORMANCE

The laser power stored in the optical cavity was estimated from the transmitted power. Figure 5 shows a typical stored power variation in the optical cavity. The average laser power

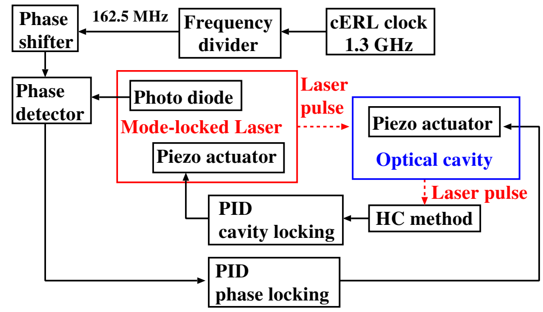

Figure 3: Block diagram of the feedback system.

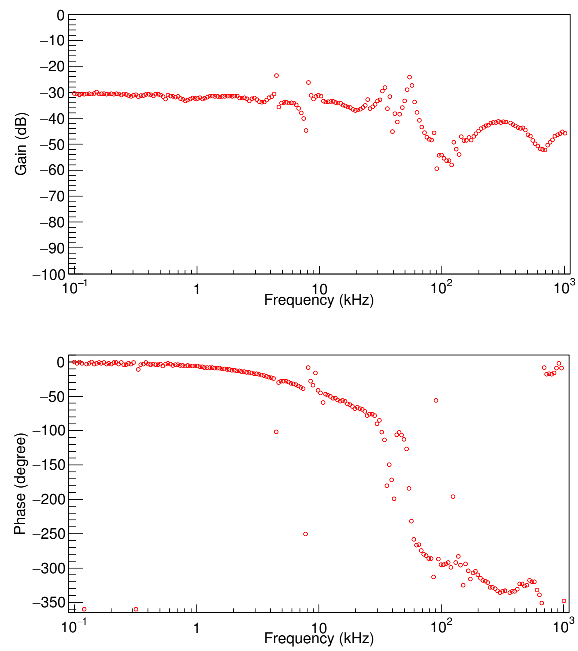

Figure 4: The measured frequency response of the piezo actuator.

was 6.4 kW with an RMS fluctuation of 0.4 kW. The power enhancement factor of the optical cavity was estimated to be 320 with an input power of 20 W. This enhancement factor was lower than the original design value because we chose the lower resonance peak. The timing stability between the laser pulse and electron bunch was monitored with a phase detector used for the phase-locking feedback. Figure shows the statistical variation of the phase. The width of the distribution was 11.9 mrad, which corresponded to an RMS of 11.7 ps. The phase variation is somewhat greater than the electron bunch length, 2 ps, and the injected laser pulse width, 5.65 ps. The laser parameters are summarized in Table 3.

Table 3: Parameters of the Laser in the Optical Cavity at the LCS Experiment

Wavelength [nm]	1064
Pulse energy [μJ]	40
Pulse width (ps, rms)	5.65
Collision angle	18
Spot size at the IP (σ_x/σ_y) [μm]	24/32
Spot size on mirrors (σ_x/σ_y) [mm]	0.7/0.6

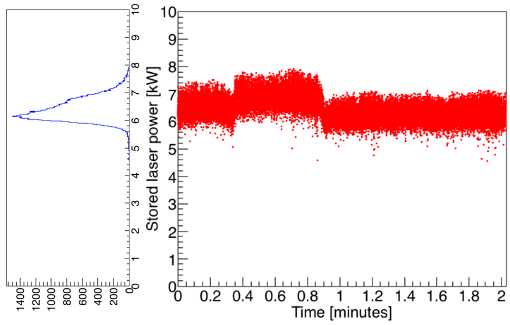

Figure 5: Stability of the stored laser power in the optical cavity.

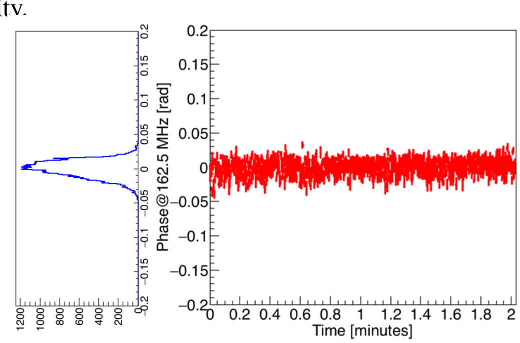

Figure 6: Stability of the laser phase in phase locking feedback.

Frequency Drift

When laser beam was accumulated, it was confirmed that the temperature rise of the optical cavity. The repetition rare is shifted by changing the cavity length with increased the cavity temperature. Therefore, long piezo actuator which is attached the cavity mirror holder is used to fix the cavity length. The long piezo actuator has a stroke of approximately 20 μm, which corresponds to a repetition rate of approximately 2 kHz. The temperature dependence of repetition rate was measured to be about -2 kHz/°C. It was almost consistent with the thermal expansion coefficient of SUS304. Therefore, temperature changes of the cavity should be less than 1°C to keep synchronization to the accelerator. We found that change of cavity length by thermal expansion was strongly dependent on the scattering loss of the cavity mirror. Figure 7 shows a example of changes in the frequency of the optical cavity. We confirmed the reduction in frequency drift by mirror cleaning.

X-RAY GENERATION EXPERIMENT

We briefly describe the LCS experiment in the cERL. The LCS X-rays were transported to an experimental room through a vacuum tube. An X-ray detector, silicon drift detector (SDD), was located 16.6 m away from the IP. The detector has an aperture with a diameter of 4.66 mm, and the opening angle was 0.14 mrad.

The central energy and energy width of the LCS signal were measured to be 6.86±0.01 keV and 210±2 eV in FWHM, respectively, as raw data. The energy resolution of the detector was estimated to be 152 eV at 6.86 keV in RMS from the peak width in the calibration. We estimated the actual spectrum width to be 145±3 eV by subtracting the contribution of the detector's resolution. The LCS signal rate was measured to be 8560 count/s with the detector.

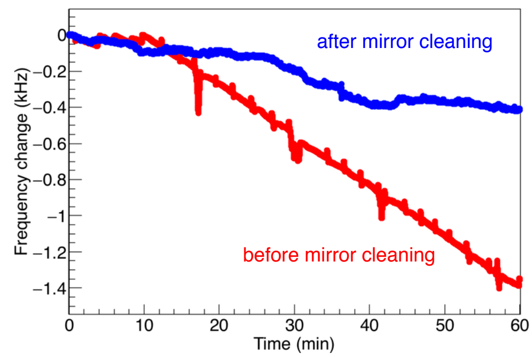

Figure 7: Measurement of changes in the frequency of the optical cavity.

The transmittance of the two beryllium windows, which are installed at both ends of the LCS beamline, was 81% in total. The distance of the beryllium window and the SDD was 5 cm. The transmittance of 7-keV X-rays in air was 90%. Considering the aperture of the SDD, the total flux at the IP was estimated to be 1.5×10^8 photons/s from the measurement result at the SDD.

SUMMARY

We have been developing ERL-based LCS source using a optical cavity at cERL. For improving the photon flux, the cavity feedback system has some issue. In addition to reduction of vibration and acoustic noise, widening the feedback bandwidth are promising way. Low-scattering loss of the cavity mirror is the key for stabilization of the cavity length keep synchronizing the laser pulse with the accelerator.

ACKNOWLEDGEMENT

This work was supported by Photon and Quantum Basic Research Coordinated Development Program from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

REFERENCES

[1] R. Nagai *et al.*, in *Proc. IPAC'15*, pp. 1607–1609.

[2] T. Obina *et al.*, in *Proc. IPAC'16*, pp. 1835–1838.

[3] T. Akagi *et al.*, in *Proc. IPAC'14*, pp. 2072–2074.

[4] R.W.P. Drever *et al.*, "Laser phase and frequency stabilization using an optical resonator", *Appl. Phys. B*, vol. 31, pp. 97–105, 1983.

[5] A. Börzsönyi *et al.*, "External cavity enhancement of picosecond pulses with 28,000 cavity finesse", *Appl. Opt.*, vol. 52, pp. 8376–8380, 2013.