DEVELOPMENT OF PULSED-LASER SUPER-CAVITY FOR COMPACT X-RAY SOURCE BASED ON LASER-COMPTON SCATTERING*

K. Sakaue,† M. Washio, Waseda University, Tokyo, Japan
S. Araki, M. Fukuda, Y. Higashi, Y. Honda, T. Taniguchi, N. Terunuma, J. Urakawa, KEK, Ibaraki, Japan
N. Sasao, H. Yokoyama, Kyoto University, Kyoto, Japan
M. Takano, Saube, Ibaraki, Japan

Abstract

A compact and high quality x-ray source is required from various fields, such as medical diagnosis, drug manufacturing and biological sciences. Laser-Compton based x-ray source that consist of a compact electron storage ring and a pulsed-laser super-cavity is one of the solutions of compact x-ray source. Pulsed-laser super-cavity has been developed for a compact high brightness x-ray sources at KEK-ATF. The pulsed-laser super-cavity increases the laser power and stably makes small laser beam size at the collision point with the electron beam. Recently, 357MHz mode-locked Nd:VAN laser pulses can be stacked stably in a 420mm long Fabry-Perot cavity with 600 enhancement in our R&D. Therefore, we have planned a compact hard x-ray source using 40MeV multi-bunch electrons and a pulse stacking technology with 42cm Fabry-Perot cavity. (LUCX Project at KEK) The photon flux is multiplied with the number of bunches by using multi-bunch beam and super-cavity. Development of the super-cavity and present result of LUCX will be presented at the conference.

INTRODUCTION

Recently, x-rays from syncrotron radiation (SR) is widely used and produced a number of results in various fields, for example, medical diagnosis, biological sciences, material sciences and so on. However, SR x-rays is generated by the huge facility as SPring-8, therefore the use is limited by the operation schedule and the number of users. On these backgrounds, a compact x-ray source has been strongly required and studied in many laboratories. In 1997, Huang and Ruth proposed a compact laser-electron storage ring (LESR) for electron beam cooling or x-ray generation.[1] In this proposal, each electrons and photons are storaged in storage ring and super-cavity, respectively, and therefore electrons and photons continuously interact and generate a high flux x-rays through the laser-Compton process.

We have developed a laser-wire beam profile monitor for measuring the electron-beam emittance at KEK-ATF. This monitor is based on the laser-Compton scattering with a laser light target. A thin and intense laser target is produced by exciting a Fabry-Perot optical cavity with a cw laser. [2] We proposed to apply for pulsed-laser stacking to achieve the high peak power photon target. To use this scheme, the high peak power laser in super-cavity is scattered by the electron beam in storage ring continuously, and generate a high quality and high flux x-rays up to 10^{14}photons/sec.[3]

LUCX PROJECT IN KEK-ATF

At first, we are performing a proof-of-principle experiment of laser-Compton scattering between pulsed-laser super-cavity and multi-bunch electron beam before using compact ring at KEK-ATF. We call this linac based x-ray source, ”LUCX” (Laser Undulator X-ray source).

In Table 1, parameters of the interaction particles, electron beam and laser beam, that have been already achieved are described.

Table 1: Parameters of interaction particles at LUCX

Electron		Laser	
RF Rep.	12.5Hz	Crystal	Nd:VAN
Energy	40MeV	Wavelength	1064nm
Pulse Rep.	357MHz	Laser Freq.	357MHz
Bunch Num.	100/train	Enhancement	630
Charge	0.5nC/bunch	Power	2.45kW
Bunch length	20ps	Pulse width	7ps
Beam size	X:80μm	Waist size	X:89μm
	Y:40μm		Y:89μm
Collision angle		20degrees	

Electron beam (Ref[4]) and laser parameters are the measured value, that have been already achieved. The detail of laser beam parameters will be mentioned in the next section. It is noted that a bunch length and a pulse width is in FWHM, and a beam size and a waist size is in RMS.

Expected X-rays in LUCX

Figure 1 shows the beam line layout of LUCX. As shown in Figure 1, the accelerator is consist of photo-cathode RF-Gun and 3m-long linac to accelerate a multi-bunch electron

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† kazu-kazu-kazu@suou.waseda.jp

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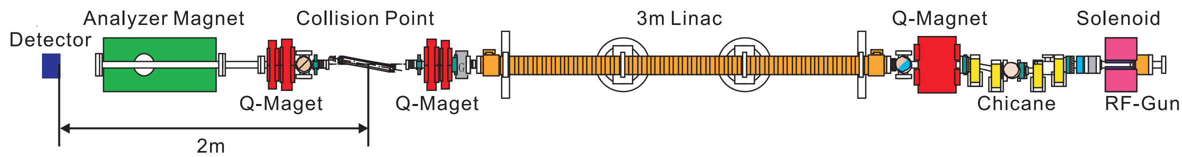

Figure 1: LUCX 40MeV beam line layout

beam. Laser-electron interaction point is located between the doublet quadrupole magnet to focus at the interaction point and to re-focus a diverging electron beam. Downstream of the interaction point, electrons are bended toward the earth by a right-angle analyzer magnet to separate the electrons from the scattered photons and damped after an energy monitor system. According to the distance between interaction point and x-ray detector of about 2m and the aperture of Be window, x-rays within 10mrad scattered angle can be extracted. Using 100 bunches/train multi-bunch electrons and pulsed-laser super-cavity, the number of interaction is one hundred times larger than as usual.

In LUCX, we are planning to generate 33keV high flux x-rays using 40MeV multi-bunch electrons and 1064nm laser light in the super-cavity. In medical application, around 33keV x-ray is used for a contrast diagnosis. 33keV is the energy of K-edge of a contrast medium, iodine (I). Figure 2 shows the estimated energy of x-rays at LUCX and attenuation coefficient of iodine. The blue line shows

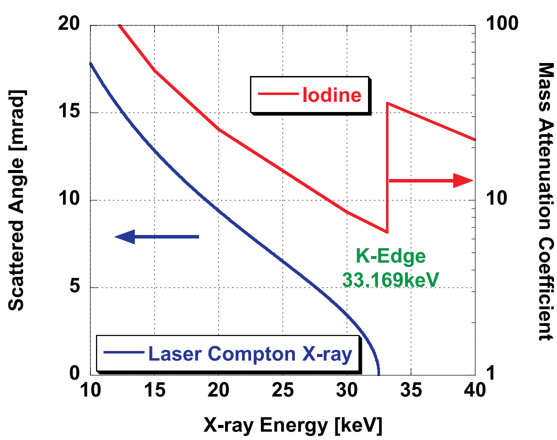

Figure 2: Laser undulator x-ray energy at LUCX

the energy of generated x-rays as a function of scattered angle, and the red line shows the attenuation coefficient of iodine. As shown in Figure 2, the energy of scattered photons is around 33keV, that attenuation of iodine is sharply changed (K-edge).

Expected number of x-rays is able to be calculated by Table 1. Total number of photons is about 40photons/pulse, and considering that the detector with 5mrad aperture, about 8photons/pulse can be detected. To take parameter of LUCX accelerator, the bunch number of 100/train and RF repetition of 12.5Hz, into consideration, we will be able to detect about 1×10^4photons/sec.

PULSED-LASER SUPER-CAVITY

Phase Noise of Pulsed-Laser

Coherent storage of a laser light in an optical cavity has been commonly used with a CW laser beam.[2] We have been developing the high finesse super-cavity to be used in this project.[5] In pulsed-laser case, the length of mode-locked cavity (L_{laser}) and super-cavity (L_{cav}) should be equal with less than nano-meter accuracy.[5]

$$| L_{laser} - L_{cav} | \ll 1nm \tag{1}$$

Because of this strict requirement, we use piezo actuator to control both cavity length.

The cavity finesse can be determined by the tuning accuracy of two cavity length (Eq.1), that is practically limited by ”the phase noise” of a mode-locked laser and an RF reference oscillator, and ”the resonant frequency” of a piezo actuator. The measurement results of phase noise is shown in Figure 3 The laser is High-Q Laser Product, Nd:VAN with passively mode-locked using SESAM, that repetition frequency is 357MHz, wavelength is 1064nm, power is above 6W and pulse duration is 7ps(FWHM).

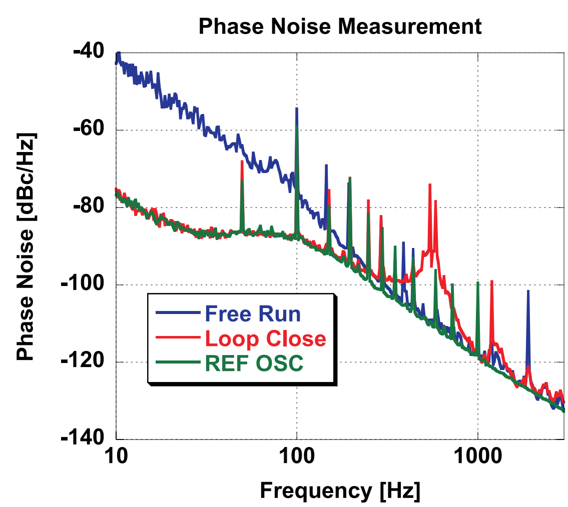

Figure 3: Phase Noise Measurement of Mode-locked Laser

In this figure, the green line shows the phase noise of reference RF oscillator, the blue and green line show the phase noise of mode-locked laser on free running and phase locked feedback, respectively.

As shown in Figure 3, the phase noise of a mode-locked laser is reduced by phase locking feedback. On the phase locking (red line), the resonant peak of piezo actuator is appeared around 0.8kHz. The noise of cavity length can be calculated from this phase noise distribution, that is about 0.1nm in RMS. This value shows the good agreement with a feedback calculation by MATLAB, and this noise can be reduced using a lower phase noise reference oscillator and an optimum piezo actuator with high frequency response or other material that can control the cavity length or the laser phase. For the reason for stable operation of super-cavity, we chose a cavity finesse of about 2000.

Measurement of Super-Cavity Parameters

As a result of phase noise measurement and piezo characterization, we determined to use a reflectivity of 99.7% mirror as input and 99.9% mirror as output. The measurement results of cavity parameter is shown in Table 2

Table 2: Measurement Results of Super-Cavity Parameters

Transmittance of Input	Transmittance of Output	Finesse	Waist Size
0.221%	0.071%	1889.9	89.2μm

Transmittance is measured by transmitted laser power, finesse is by the decay method using pockels cells and waist size is measured by the phase advance between the two different cavity mode. The enhancement factor is calculated by finesse that is about 750. These values are consistent with the design value of super-cavity.

As the next step, we performed a cavity resonant feedback test that is for confirming the laser power in the super-cavity. The feedback error signal is produced by the spatial mode interference (Ref[6]). The waveform of feedback error signal and the behavior of feedback are shown in Figure 4.

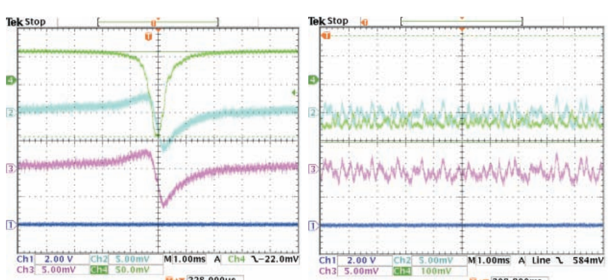

Figure 4: Waveforms of Cavity Resonant Feedback

In Figure 4, green and pink waveform show the transmitted power from the cavity and feedback error signal, respectively. Left figure shows the behavior in scanning the cavity length and right is closing the feedback loop. As you can see in Figure 2, the feedback is closed around the top of the resonant peak and achieved the maximum laser power in super-cavity.

As the result of these experiments, we have already achieved 2.4kW laser power in the super-cavity, that is measured by the transmitted power from the cavity and transmittance of output mirror. The parameters of this measurement is shown below.

Table 3: Result of Pulse Enhancement in Super-Cavity

Input Power	Power in Cavity	Enhancement
4.05W	2.45kW	605

As shown in Table 3, 4.05W input laser is enhanced to 2.45kW in the super-cavity that the enhancement factor is above 600. The measured enhancement factor is slightly less than the calculated value of 750. This difference is come from the matching efficiency through the input laser to cavity mode and the jitter of the cavity length that cannot be reduced by the piezo feedback.

For the stably operation of super-cavity, we performed a long running test of super-cavity with feedback. As a result of this, it is confirmed that our super-cavity system can operate over 10 hours without failing the resonant feedback.

CONCLUSIONS

We plan to compact x-ray source using super-cavity for laser and storage ring for electrons. At first, proof-of-principle experiment of multi-bunch electrons and super-cavity laser light will be performed.

Pulsed-laser super-cavity has been developing at KEK-ATF. The storaged laser power of 2.45kW is already achieved using 1900 finesse super-cavity.

All system is already installed in the LUCX accelerator, therefore we are ready to collision experiment. After the summer shut down of ATF/LUCX, we will perform a collision experiment and generate a multi-pulse laser-Compton x-rays.

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