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ENHANCEMENT OF LASER-COMPTON X-RAY BY CRAB CROSSING*

Y. Koshiba†, S. Ota, R. Morita, K. Sakaue, M. Washio,
RISE, Waseda University, Tokyo, Japan
T. Higashiguchi, Utsunomiya University, Tochigi, Japan
J. Urakawa, KEK, Ibaraki, Japan

Abstract

We are going to apply crab crossing of electrons and laser photons for the enhancement of laser-Compton X-ray. Crab crossing will enable quasi-head-on collision and increase the luminosity. Therefore, it could be combined with an optical enhancement cavity without the interference of beams and cavity mirrors, leading to the generation of intense X-ray pulses. Calculation show more than fourfold luminosity will be achievable in our system, and could be larger depending on beam parameters. Although crab crossing in laser-Compton scattering has been already proposed, it has not been demonstrated yet anywhere. This will be the proof-of-principle study of the crab crossing laser-Compton scattering. In this conference, we will report our laser system based on thin-disk technology, and results of crab crossing laser-Compton scattering.

INTRODUCTION

There has been a great demand of intense and compact X-ray source. X-ray free electron laser (XFEL) based on self-amplified spontaneous emission (SASE) scheme [1] has been already realized for users at Linac Coherent Light Source (LCLS) in America, SPring-8 Angstrom Compact Free Electron Laser (SACLA) in Japan, European XFEL in Germany, and Pohang Accelerator Laboratory X-ray Free-Electron Laser (PAL-XFEL) in South Korea. These sources provide powerful (10^{33} peak brilliance) X-ray and developed new X-ray science. One of the next common goal is to make these sources compact and low cost. Laser-Compton scattering (LCS) is one of the candidates. In terms of brilliance, almost 10^{10} has been achieved [2], and exceeding 10^{12} has been designed [3]. Comparing with magnetic undulators, LCS could be explained as an "optical undulator", which the undulator period equivalent to the order of laser wavelength (~1 um) while magnetic undulator is the order of cm. Figure 1 shows the comparison of undulator radiation and LCS.

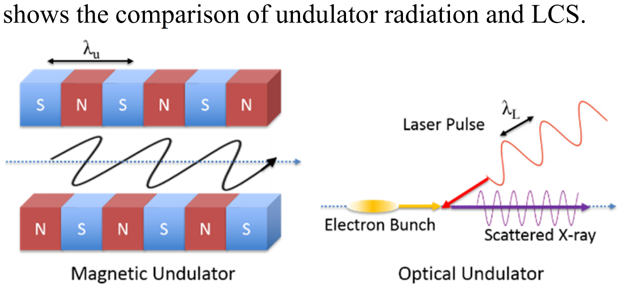

Figure 1: Comparison of undulator radiation and LCS.

When thinking of producing 1 Å photons, LCS needs only 25 MeV beam energy, while 6 GeV for undulator radiation (K=1, λu=2 cm) and 4 GeV for synchrotron radiation (ρ= 12m). Low required beam energy enables the whole system compact and low cost so that laboratories and hospitals may take care. This is the most important feature of LCS. The schematic drawing of LCS is shown in Fig. 2.

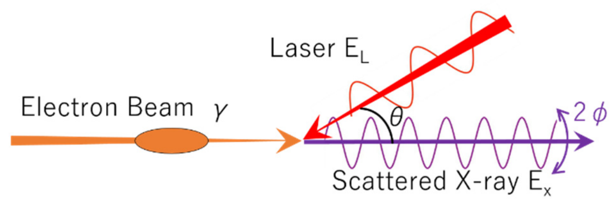

Figure 2: Schematic drawing of LCS.

γ, EL, EX, θ, ϕ represents the Lorentz factor of electron beam, energy of laser photon, energy of scattered X-ray, colliding angle, and scattering angle, respectively. The maximum X-ray energy ExMAX would be obtained along the electron beam axis ϕ=0 and written as

$$E_X^{MAX} \approx 2\gamma^2 (1+\beta\cos\theta) E_L \tag{1}$$

where β is the velocity of electrons relative to the speed of light. We can see that scattered photon energy is tunable by controlling the beam energy or the collision angle. When θ=0, i.e. head-on collision, the photon energy will be raised by a factor of 4γ2. Another important fact is that the scattered photon energy and the scattered angle are correlated. Their relation is written as

$$E_\varphi = \frac{E_X^{MAX}}{1+\gamma^2\theta^2} \tag{2}$$

Therefore, a quasi-monochromatic light could be achieved by an aperture around ϕ=0. The number of scattered photons is given by the product of cross section and luminosity.

$$N = \sigma L = \sigma P G \tag{3}$$

Since the total cross section is unchangeable once the laser wavelength and beam energy is decided, it is necessary to increase the luminosity as much as possible. Luminosity can be expressed as the product of power factor (P) and geometric factor (G) as seen in Eq. (3). Power factor is the product of the number of electrons in a bunch and the number of photons in a laser pulse. Geometric

* Work supported by Grant-in-Aid for JSPS Research Fellow.
† email address: advanced-yuya@asagi.waseda.jp

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$$G = \frac{1 + \beta \cos\theta}{2\pi \sqrt{\sigma_y^2 + \sigma'^2_y} \sqrt{\sigma_x^2 (\beta + \cos\theta)^2 + \sigma'^2_x (1 + \beta\cos\theta)^2 + \left(\sigma_z^2 + \sigma'^2_z\right)\sin^2\theta}} \quad (4)$$

factor is written as Eq. (4) when assuming Gaussian for both electron bunch and laser pulse. Here σ_x, σ_y, σ_z represents the electron bunch sizes of horizontal, vertical, and longitudinal respectively, and prime ones are those of laser pulse. Let us substitute parameters shown in Table 1, our system's parameters, into Eq. (3).

Table 1: Parameters of Electron Beam and Laser Pulse

	Electron Beam	Laser Pulse
Energy	4.2 MeV	1.2 eV(1030 nm)
Intensity	40 pC	10 mJ
Transverse Size	40 µm	50 µm
Duration	3 ps(rms)	0.43 ps(rms)

Then the luminosity dependence on collision angle would be shown in Fig. 3.

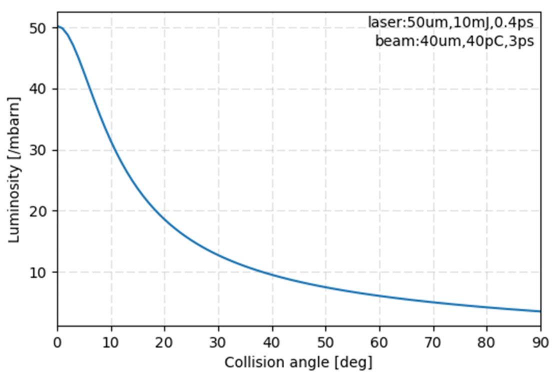

Figure 3: Luminosity as a function of collision angle.

We can see that the luminosity is maximum when collision angle is zero, i.e. head-on collision and monotonically decrease as collision angle increase. Despite this fact, head-on collision is hard to realize especially with an optical enhancement cavity [4], considering the interference of cavity mirrors and electron beam path. In addition, scattered X-ray must get across a mirror. This might cause damages to the mirror and distort the X-ray profile. Due to these facts, quite a few LCS X-ray sources have a certain colliding angle which causes luminosity loss [5]. One method to overcome this problem is the crab crossing.

CRAB CROSSING LCS

Effect of Crab Crossing

Crab crossing is a proven technique in colliders that allows an angle crossing without luminosity loss. Figure 4 depicts the schematic of crab crossing.

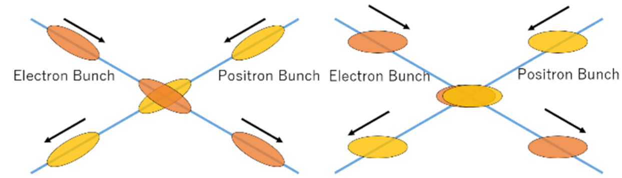

Figure 4: Schematic drawing of crab crossing.

Luminosity is increased by tilting the bunches. Quasi head-on collision is realized at the interaction point and the number of particle reactions increase in colliders. In LCS, since it is a collision of electron bunch and laser pulse, we are planning to tilt only the electron beam with an rf-deflector. Figure 5 shows the schematic of crab crossing LCS.

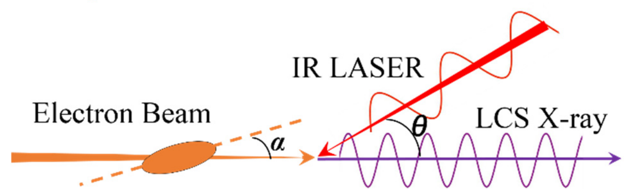

Figure 5: Schematic of crab crossing LCS.

Luminosity is maximized when the tilt angle α is half of collision angle [6]. The enhancement ratio between ordinary crossing and crab crossing would be

$$\frac{G_{crab}}{G_{non-crab}} = \sqrt{\frac{\left(\sigma_x^2 + \sigma'^2_x\right)\cos^2\frac{\theta}{2} + \left(\sigma_z^2 + \sigma'^2_z\right)\sin^2\frac{\theta}{2}}{\sigma_x^2 + \sigma'^2_x\cos^2\frac{\theta}{2} + \sigma'^2_z\sin^2\frac{\theta}{2}}} \quad (4)$$

Using those parameters listed in Table 1, the enhancement ratio (crab ratio) in our system is shown in Fig. 6.

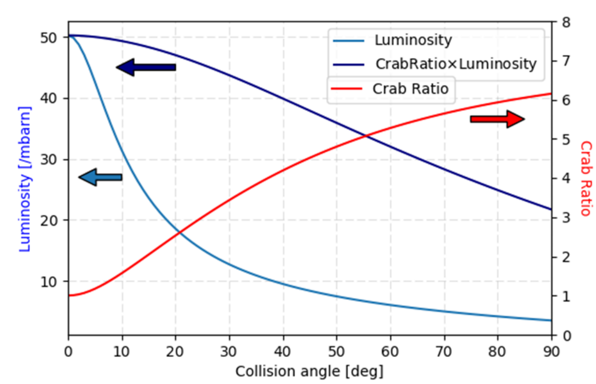

Figure 6: Enhancement ratio of crab crossing.

We are planning to conduct the proof of principle experiment at 45 degrees and the expected enhancement ratio is 4.15. By comparing the blue lines, we can say that the luminosity is compensated by crab crossing. The laser pulse duration has a significant effect to the crab ratio. The effect of pulse duration of colliding laser is shown in Fig. 7.

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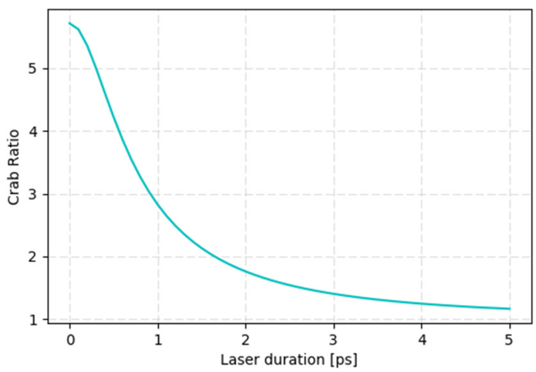

Figure 7: Pulse duration and enhancement ratio.

Short and intense pulse makes crab crossing more effective. Concerning this fact, we are developing a laser system based on Yb fiber oscillator and Yb:YAG thin-disk regenerative amplifier for crab crossing LCS.

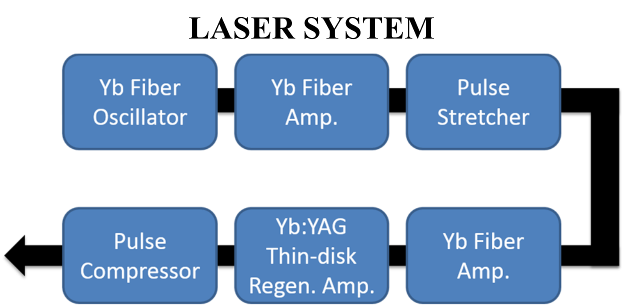

Figure 8: Schematic of laser system.

We are developing a laser system suitable for the demonstration of crab crossing LCS, based on chirped pulse amplification (CPA) as shown in Fig. 8. We aim to generate 10mJ, 430fs laser pulse. Generation of femtosecond pulse is made by an Yb fiber laser oscillator based on nonlinear polarization rotation, also known as ANDi laser [7]. The measured pulse duration was 1ps by an autocorrelator. After a preamplifier, the pulse is stretched with a diffraction grating with 1739 grooves to 150ps. After another fiber amplifier, it is amplified by an Yb:YAG thin-disk regenerative amplifier. Compared to conventional rod media, thin-disk media has advantages of heat dissipation so that high beam quality is achieved together with high power. A disk from Dausinger + Giesen GmbH is used. The schematic of regenerative amplifier is shown in Fig. 9.

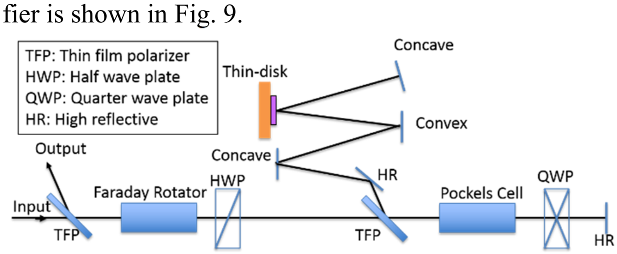

Figure 9: Schematic of thin-disk regenerative amplifier.

Our preliminary test with an 88W CW LD pump show that the small signal gain (double pass gain) is 1.14. Note that the mirrors inside the multi-pass pump module were not high-reflection (HR) coated. With this setup, we have succeeded in generating 0.23mJ (10kHz), 0.8mJ (1kHz) pulse. We also successfully confirmed the regenerative amplification of the pulse by the build-up waveform of an oscilloscope, which is shown in Fig. 10.

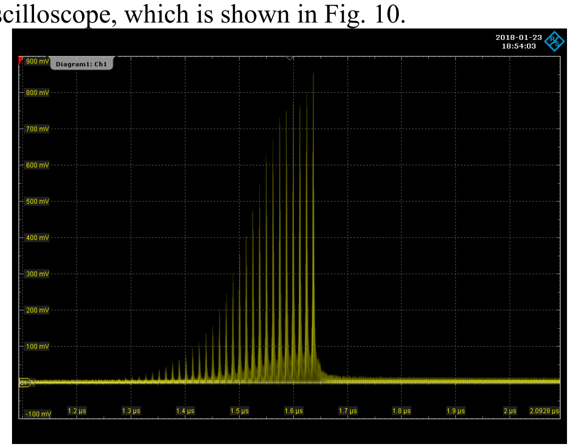

Figure 10: Pulse build-up in regen amplifier.

Encouraged by these results, we are now upgrading our module, which means replacing non-coated mirrors to HR coated ones and replacing CW LD to a pulsed LD with higher power.

CONCLUSION

We are planning to demonstrate the crab crossing LCS in our compact accelerator system in Waseda University. Luminosity increase is likely to be more than fourfold when the colliding angle is 45 deg. We have finished preliminary tests of Yb:YAG thin-disk regenerative amplifier and currently working on upgrade to generate 10mJ, 430fs laser pulse. The demonstration of crab crossing LCS will be conducted soon.

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