LUMINOSITY INCREASE IN LASER-COMPTON SCATTERING BY CRAB CROSSING METHOD

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Abstract

In collider experiments, such as KEKB, crab crossing method is a promising way to increase the luminosity. We are planning to apply crab crossing to laser-Compton scattering (LCS), a collision of electron beam and laser, to achieve a higher luminosity leading to a higher flux X-ray source. It is well known that the collision angle affects the luminosity. It is the best when the collision angle is zero, head-on collision, for a higher luminosity but difficult to construct such system especially when using an optical cavity for laser. Concerning this difficulty, we are planning crab crossing by tilting the electron beam using an rf-deflector. Although crab crossing in LCS has been already proposed [1], nowhere has demonstrated yet. We are going to demonstrate and conduct experimental study with our compact accelerator system in Waseda University. In this conference, we will report mainly about expected results of crab crossing LCS.

INTRODUCTION

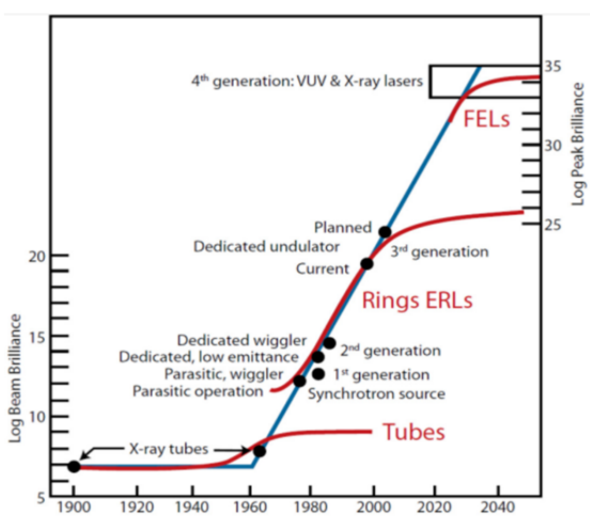

Figure 1: Development of X-ray brilliance [2].

Over a century, since X-ray had been discovered by Roentgen in 1895, it has been utilized in various fields such as medical application, biological science, material science and so on. The common X-ray sources these days are X-ray tubes or synchrotron facilities. X-ray tubes are compact and easy to use so that they are most widely used. Regarding the brilliance, X-ray tubes are relatively low. On the other hand, synchrotron facilities provide X-rays with higher brilliance typically around 10^{15} (from bending magnets), but requires beam energy of GeV and a large ring accelerator. Figure 1 shows the development of X-ray brilliance [2]. The most powerful X-ray source is the XFEL and has achieved wavelength below 1 Å with pulse length less than 100 fs [3]. LCS X-ray (LCS-X) sources are comparable in brilliance to the second generation synchrotron light sources but significantly downsized and cost-effective.

Laser-Compton Scattering

LCS is a phenomenon generating higher energy photons through collisions of relativistic electrons and long wavelength laser photons. The scattered photons would be in the region of soft X-ray to gamma ray. Figure 2 shows the schema of LCS.

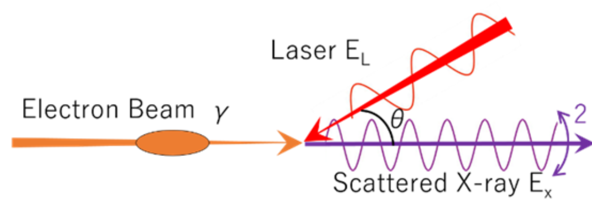

Figure 2: Schema of LCS.

γ, E_L, E_X, 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 E_x^{MAX} would be obtained along the electron beam axis $\phi=0$ and written as

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

where β is the velocity of electrons relative to the speed of light. We can see that the X-ray energy is tunable by the electron beam energy and the colliding angle. The total number of scattered photons is given by the product of the total cross section of Compton scattering (σ) and luminosity (L).

$$N = \sigma L = \sigma P G \tag{2}$$

Since the total cross section is nearly 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. (2). Power factor is the product of the number of electrons in a bunch and the number of photons in a laser pulse. The

$$G = \frac{1+\beta\cos\theta}{2\pi\sqrt{\sigma_y^2+\sigma'^2_y}\sqrt{\sigma_x^2(\beta+\cos\theta)^2 + \sigma'^2_x(1+\beta\cos\theta)^2 + \left(\sigma_z^2+\sigma'^2_z\right)\sin^2\theta}} \tag{3}$$

geometric factor is expressed as Eq. (3) when assuming a Gaussian distribution 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 colliding angle would be shown in Fig. 3.

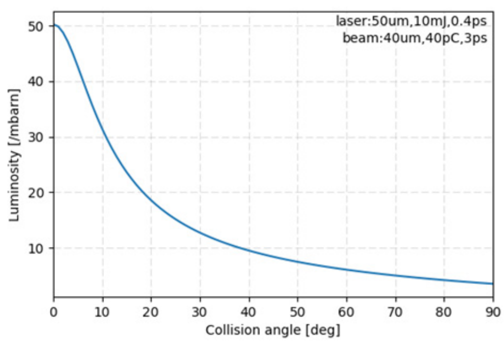

Figure 3: Luminosity dependence on colliding angle.

Maximum luminosity could be achieved when the colliding angle is zero, i.e. head-on collision. Despite this fact, head-on collision is hard to construct especially with an optical enhancement cavity [4], considering the interference of cavity mirrors and electron beam path. In addition, scattered X-rays must get across a mirror. This might cause damages to the mirror. Due to these facts, quite a few LCS X-ray sources have a certain colliding angle which causes luminosity loss [e.g., 5]. One method to overcome this problem is the crab crossing.

CRAB CROSSING LCS

Effect of Crab Crossing

Crab crossing method is adopted in colliders to increase the luminosity. Figure 4 depicts the schema of it.

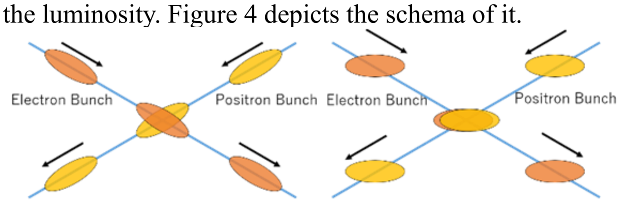

Figure 4: Schema of crab crossing.

Quasi-head-on collision is realized by tilting the beams. We are planning to tilt only the electron bunch with an rf-deflector. Our rf-deflector is a 2-cell standing wave cavity which can kick the electrons transversely with the TM210 mode magnetic field. Figure 5 illustrates the crab crossing LCS.

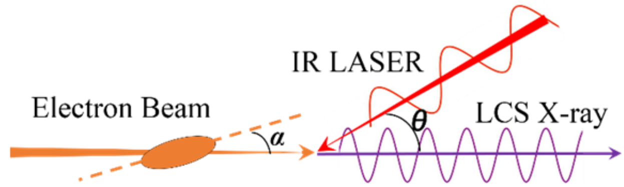

Figure 5: Schema of crab crossing LCS.

It is the geometric factor which would be enlarged by tilting the electron bunch [1]. Here, let us introduce the term 'crab angle' for the tilting angle of electron bunch. The geometric factor under $\beta\sim 1$ would be expressed as

$$G(\theta,\alpha)=\frac{1}{2\pi\sqrt{\sigma_y^2+\sigma'^2_y}\sqrt{f_e(\theta,\alpha)+f_l(\alpha)}} \tag{4}$$

$$f_e(\theta,\alpha)=\sigma_x^2\left(\frac{\cos(\alpha-\theta)+\cos\alpha}{1+\cos\theta}\right)^2+\sigma_z^2\left(\frac{\sin(\alpha-\theta)+\sin\alpha}{1+\cos\theta}\right)^2 \tag{5}$$

$$f_l(\alpha)=\sigma'^2_x+\sigma'^2_z\left(\frac{\sin\theta}{1+\cos\theta}\right)^2 \tag{6}$$

where α represents the crab angle. From these relations, the geometric factor would be maximized when crab angle is half of the colliding angle. In this situation, Eq. (4) would be

$$G(\theta,\frac{\theta}{2})=\frac{1}{2\pi\sqrt{\sigma_y^2+\sigma'^2_y}\sqrt{\sigma_x^2\sec^2\frac{\theta}{2}+\sigma'^2_x+\sigma'^2_z\tan^2\frac{\theta}{2}}} \tag{7}$$

and the 'crab ratio' would be

$$\frac{G(\theta,\theta/2)}{G(\theta,0)}=\sqrt{\frac{\left(\sigma_x^2+\sigma'^2_x\right)\cos^2\frac{\theta}{2}+\left(\sigma_z^2+\sigma'^2_z\right)\sin^2\frac{\theta}{2}}{\sigma_x^2+\sigma'^2_x\cos^2\frac{\theta}{2}+\sigma'^2_z\sin^2\frac{\theta}{2}}} \tag{8}$$

Equation (8) gives us the maximum enhancement ratio between ordinary crossing and crab crossing. Using those parameters listed in Table 1, relationship between crab ratio and colliding angle in our system is shown in Fig. 6.

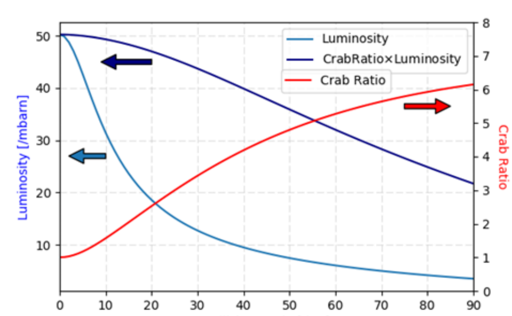

Figure 6: Crab ratio as a function of colliding angle.

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A larger colliding angle would result in larger increase of luminosity. By comparing the blue lines, we can say that the luminosity loss is compensated by crab crossing.

CAIN Simulation

Expected spectra were calculated by a Monte-Carlo code CAIN. Figure 7 shows the spectra of ideal head-on collision (red), 45-deg collision (blue), and 45-deg collision with crab crossing (green).

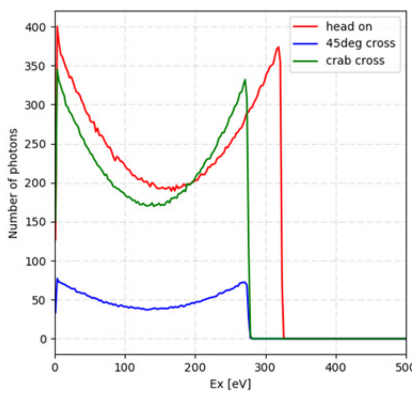

Figure 7: LCS-X spectra calculated by CAIN.

It is obvious that the number of photons increases by crab crossing. We can also see that the maximum energy of LCS-X, so called as Compton edge, does not change by crab crossing. This is because each interaction of an electron and a photon does not change just by tilting the electron bunch. The number of photons calculated are listed in Table 2.

Table 2: Scattered Photons Calculated by CAIN

(θ, α)	Number of Photons
(0, 0)	32900
(45, 0)	5573
(45, 22.5)	24940

We can confirm that the total number of generated photons in crab crossing is more than 4 times larger than that of ordinary crossing. Furthermore, crab crossing enables almost 76 % of head-on likeness, while ordinary crossing is only 17 %.

EXPERIMENTAL SETUP

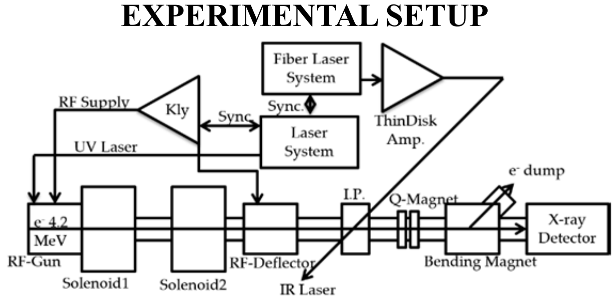

Figure 8: Setup for crab crossing LCS.

The experimental setup is shown in Fig. 8. 1.6 cell rf gun with CsTe photocathode will generate 4.2 MeV, 40pC, 3ps electron bunch. They will be focused at I.P. (Interaction point) with solenoid magnets so as to achieve higher luminosity. Rf-deflector will give crab angle to the electron bunch. Bending magnet is necessary to separate the electron beam from LCS-X. Colliding laser would be produced by Yb fiber oscillator, fiber amplifiers, and thin disk regenerative amplifier (see [6] for detail). A shorter laser pulse makes crab crossing more effective. Figure 9 shows the crab ratio as a function of laser pulse width.

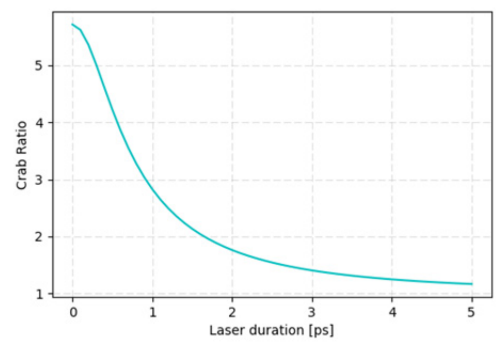

Figure 9: Crab ratio as a function of laser pulse width.

We are going to use MCP (Micro Channel Plate) for X-ray detector. We have already done background measurement by transporting electron beam (without electron-laser collision) and confirmed that it is sufficiently low.

SUMMARY

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. Encouraged by such good prospects, we are now concentrating on constructing the thin disk regenerative amplifier as a colliding laser, favourable for the crab crossing LCS.

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