LUMINOSITY INCREASE IN LASER-COMPTON SCATTERING BY CRAB CROSSING METHOD

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Abstract

In collider experiments such as KEKB, crab crossing is a promising way to increase the luminosity. We are planning to apply crab crossing to laser-Compton scattering (LCS), which is a collision of electron beam and laser, to gain a higher luminosity leading to a higher brilliance X-ray source. It is well known that the colliding angle between electron beam and laser affects the luminosity. It is the best when the collision angle is zero, head-on collision, to get the highest luminosity but difficult to construct such configuration especially when using an optical enhancement cavity. 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 studies at our compact accelerator system in Waseda University. In this conference, we will report mainly about expected results of crab crossing LCS.

INTRODUCTION

Nowadays, X-rays are used in various fields such as medical application, biological science, material science and so on. In most cases, X-rays are produced by means of X-ray tubes or synchrotron facilities. X-ray tubes are easy to use and compact, but the brilliance is around 10^8, relatively low. On the other hand, synchrotron radiation X-rays have high brilliance around 10^{16}, but it needs a GeV class electron beam with a kilometer-long storage ring. Laser-Compton scattering (LCS) X-ray source lies between these two. In other words, it is expected as a compact high brilliance X-ray source. LCS X-ray sources are more compact than synchrotron sources because the energy required is MeV order. In terms of brilliance, $>10^{12}$ has been designed [2].

In Waseda University, LCS experiments had been conducted for the purpose of soft X-ray microscopes for biological observations [3]. Also with the collaboration of KEK, LUCX (Laser Undulator Compact X-ray) has been developing using a 4-mirror optical enhancement cavity [4]. In this report however, we will discuss about crab crossing method in LCS.

Accelerator System in Waseda University

We have been developing a compact (2×3m) S-band accelerator system based on a photocathode rf electron gun, shown in Fig. 1. The rf gun structure is based on BNL GUN-IV and can generate 3π mm-mrad, 5MeV, 10ps (FWHM) electron bunch with a 10MW klystron.

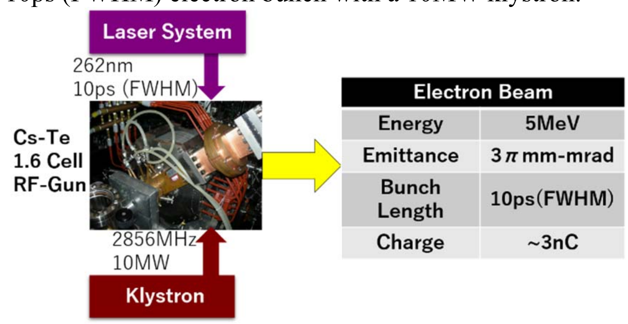

Figure 1: Accelerator system in Waseda University.

Several studies are done using this system such as pulse radiolysis experiment for radiation chemical reactions [5], coherent terahertz Cherenkov radiation [6], ultra-short bunch length measurement using a rf-deflector [7], etc.

Laser-Compton Scattering

LCS (or inverse Compton scattering) 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.

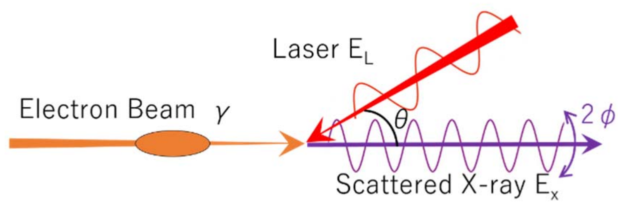

Figure 2: Schema of LCS.

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

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

where β is the velocity of electrons relative to the speed of light. We can see that the maximum 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).

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

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

Since the total cross section is nearly unchangeable when the laser wavelength and electron beam energy is decided, it is important to increase the luminosity for generating intense X-rays. 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 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	4.2MeV	1.2eV(1030nm)
Intensity	40pC	10mJ
Transverse Size	100µm	50µm
Duration	10ps(FWHM)	1ps(FWHM)

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

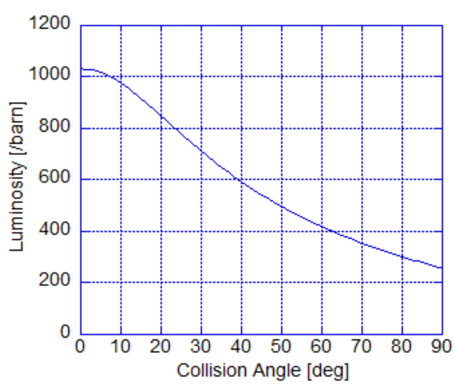

Figure 3: Luminosity dependence on colliding angle.

Maximum luminosity could be achieved when the colliding angle is zero, i.e. head-on collision. In spite of this fact, head-on collision is hard to construct especially with an optical enhancement cavity, since the scattered X-rays must get across a mirror. This might also cause damages to the mirror. Due to these facts, quite a number of LCS X-ray sources have a certain colliding angle which causes luminosity loss. One method to overcome this problem is the crab crossing.

CRAB CROSSING LCS

Effect of Crab Crossing

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

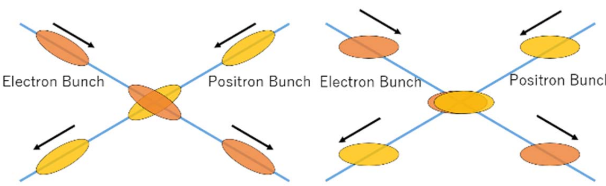

Figure 4: Schema of crab crossing.

The collision could be made close to a head-on collision by tilting the beams. We are planning to tilt only our 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.

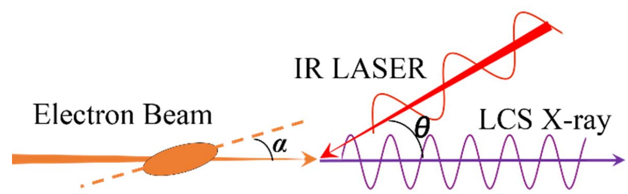

Figure 5: Schema of crab crossing LCS.

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 β~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 is shown in Fig. 6. A larger colliding angle would result in larger increase of luminosity.

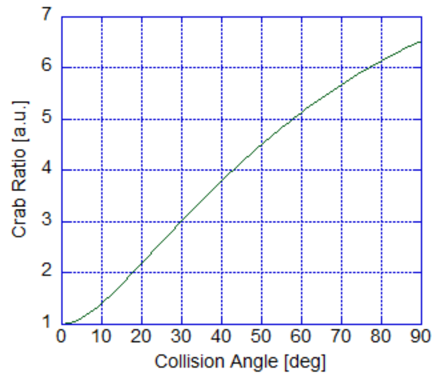

Figure 6: Crab ratio as a function of colliding angle.

CAIN Simulation

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

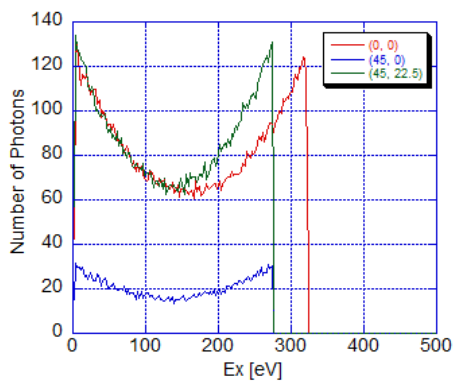

Figure 7: LCS spectra calculated by CAIN.

It is clear that the number of photons increases by crab crossing. We can also say that the maximum energy of LCS X-ray, 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)	10800
(45, 0)	2245
(45, 22.5)	9631

We could 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 90% of head-on likeness, while ordinary crossing is only 20%.

EXPERIMENTAL SETUP

The expected experimental setup is shown in Fig. 8.

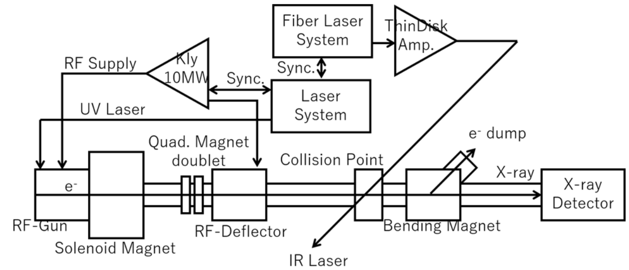

Figure 8: Beamline for crab crossing LCS.

Electron bunch will be focused with a solenoid magnet and a quadruple doublet so as to achieve higher luminosity. Rf-deflector will provide crab angle to the electron bunch. Bending magnet is necessary to separate the electron beam from LCS X-ray. Colliding laser would be produced by fiber oscillator, fiber amplifiers, and thin disk regenerative amplifier. The colliding angle would be 45deg. We are going to use MCP (Micro Channel Plate) for X-ray detector. We have already done background measurement 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 45deg. Encouraged by such good prospects, we are now concentrating on constructing the laser system for crab crossing LCS.

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