DEVELOPMENT OF SOFT X-RAY SOURCE USING LASER COMPTON SCATTERING

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Abstract

Soft X-ray source using a laser Compton scattering between a 5MeV electron beam and a Nd:YLF laser light (1047nm) has been developed at Waseda University. Generated X-ray energy was analytically calculated to be 435eV in the 20° interaction, 333eV in the 60° interaction and 222eV in the 90° interaction with the energy band - width of less than 0.39%. The energy of these X-ray is included in the range of “water window” so that these X-ray is useful for the biological observation. The maximum number of x-ray is analytically estimated to be 1.8×10^3 at 435eV with 0.39% energy band-width. As the preliminary experiment, Timing adjustment between the electron beam and the laser light and background measurements of detector were performed.

1 INTRODUCTION

Short-pulsed X-ray source is required in various research fields, such as material and medical science. To meet these demands, R&D on the next-generation light source has been initiated at several laboratories in the world. One of the most promising approaches to short-pulsed X-ray sources is the Laser Synchrotron Source (LSS), which is based on laser Compton scattering. Laser Compton scattering between a relativistic electron beam and a laser light has been investigated as a technique of high bright X-ray generation [1-3]. The LSS has many features, which are tunability of the wavelength, the spectrum distribution, the spatial distribution and the yield of the scattered photons. Those characteristics of scattered photons can be controlled varying the collision angle between the electron beam and the laser pulse, and by changing energy of the electron beam or wavelength of the laser light. Further, ultra-short pulsed X-ray generations were developed based on scattering between a short-bunched electron beam and a femto-second high power laser pulse in 90° interaction [4].

Soft X-rays are very useful for biological observation, because K-shell absorption edges of Oxygen, Carbon and Nitrogen, which mainly constitute of living body, are 2.332nm (531.73eV), 4.368nm (283.88eV) and 3.099nm (400.13eV), respectively [5] and those absorption edges are included in the range of “water window”. Since the absorption coefficient of water is much smaller than the protein’s coefficient in this range of “water window”, a dehydration of the specimens is not necessary. In future, the soft X-ray source will be applied to an X-ray microscopy to get the images of hydrated biological specimens without blurring caused by radiation damage and thermal diffusion.

2 X-RAY GENERATION

In the laser Compton scattering, the wavelength of generated soft X-rays can be changed by the collision angle between the electron beam and the laser lights. It is assumed that electron beam energy and incident photon energy are E_b (=γmc^2) and k_0 in the laboratory frame. The energy of scattered photons k_s is given as

$$k_s = \frac{\gamma^2 k_0 (mc^2)(1+\beta\cos\varphi)(1+\beta\cos\theta)}{mc^2 + (1+\cos\theta)(1+\beta\cos\varphi)\gamma k_0} \quad (1),$$

where $\cos\theta = (\cos\theta_s - \beta)/(1-\beta\cos\theta_s)$, angles of φ, θ, θ_s are the crossing angle in the laboratory frame, the scattered angle in the electron rest frame and the laboratory frame, respectively. From Equation (1), the maximum energy of scattered photons is given as

$$k_s(\max) = \frac{\gamma^2 k_0 (mc^2)(1+\beta\cos\varphi)(1+\beta)}{mc^2 + 2\cdot(1+\beta\cos\varphi)\gamma k_0} \quad (2).$$

Table 1 shows typical parameters of the electron beam and the laser light for the laser Compton scattering in case of our system. Figure 1 gives results of the calculation that the scattered angles versus the scattered photon energy at different collision angles with the energy of K-shell absorption edge of Oxygen, Carbon and Nitrogen. To select the energy of the generated X-rays between each K-shell absorption edges for imaging the contrast of these elements in living body, they will be collected within a few degrees along the direction of the electron beam propagation. When the collected angle is selected within 12mrad, the energy band-width is less than 0.39%.

Electron Beam		Nd:YLF Laser	
Beam Energy	5.0 MeV	Wave length	1047 nm
Beam Charge	0.5 nC/bunch	Energy	40 mJ/pulse
Bunch Length	10ps(FWHM)	Pulse length	10ps(FWHM)
Beam Size	200/200 μm	Beam SIze	60/60 μm

Table 1: Typical parameters of electron beam and Nd:YLF laser

The total numbers of produced X-ray photons by laser Compton scattering is analytically estimated using the product of the cross section of Compton scattering (σ) and Luminosity (L), which is determined by the scattering geometry of the electron beam and the laser pulse (Table 2). In the case of head-on configuration (zero crossing angle), the number of generated X-ray photons is generally maximized. As a result of the analytically estimation for the laser Compton scattering at 20°, 60°, 90° interaction angles, Table 2 shows the number of photons and averaged energy of generated X-ray within the 12mrad scattered angle due to the diameter of the circular microchannel plate (MCP) detector and the length between the interaction point and the detecting point. Figure 2 shows the differential cross section, which was derived from Klein-Nishina formula, as a function of the generated X-ray energy at difference crossing angles.

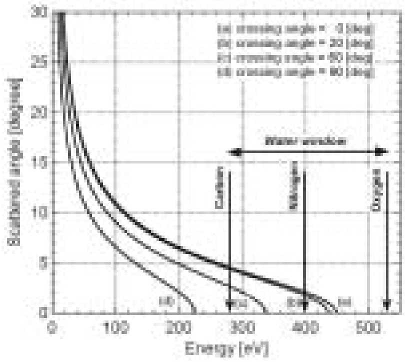

Figure 1: Angular distribution of scattered X-rays at different crossing angle and K-shell absorption edge of Carbon, Nitrogen and Oxygen.

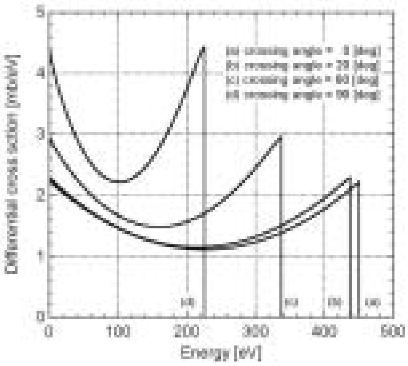

Figure 2: Differential cross section as the function of the generated X-ray energy in different crossing angles.

Crossing angle	Scattered X-ray energy	Number of photons
20°	435 eV	1.8×10^{3}
60°	333 eV	6.3×10^{2}
90°	222 eV	3.7×10^{2}

Table 2: Parameters of generated X-ray in the 20°, 60° and 90° interaction

3 X-RAY GENERATION EXPERIMENT AT WASEDA UNIVERSITY

3.1 Experimental setup

Beam line layout for X-ray generation experiment is shown in Figure 3. In our X-ray generation experiment, a stable laser light (1047nm) is scattered by the pulsed electron beam, which is produced by a photo-cathode rf-gun system. The rf-gun system is composed of the BNL type 1.6 cells S-band rf cavities with Mg cathode [6,7] and a stabilized all-solid-state laser and an rf power source. All-solid-state pico-second Nd:YLF laser is used for both an irradiation of the rf-gun cathode and the laser Compton scattering. The electron beam is emitted from the Mg photo-cathode using the 10ps UV laser light (262nm). The electron beam can be controlled very precisely changing the injection phase, the intensity and the profiles in transverse and longitudinal directions of the laser pulses. The produced electron beam is focused at a center of an interaction chamber using a solenoid magnet and the quadropole magnets. The timing jitter between the electron bunch and Nd:YLF laser light for laser Compton scattering is negligible in comparison with the pulse length of the electron beam and the laser light, since the seed of UV laser pulse for the photo-cathode illumination of the rf-gun and IR laser pulse is same seed laser light (Figure 4).

The interaction chamber for the laser Compton scattering experiment was designed to select the crossing angle, 20°, 60° and 90°, between the electron beam and the laser light. Choosing the crossing angles, the energy spectrum of the generated X-rays can be changed with constant operation of accelerator and laser system. Furthermore, the energy of generated X-rays with pulse-to-pulse can be changed by controlling the laser injection angle to the interaction chamber with combination of Pockels cells and polarizers.

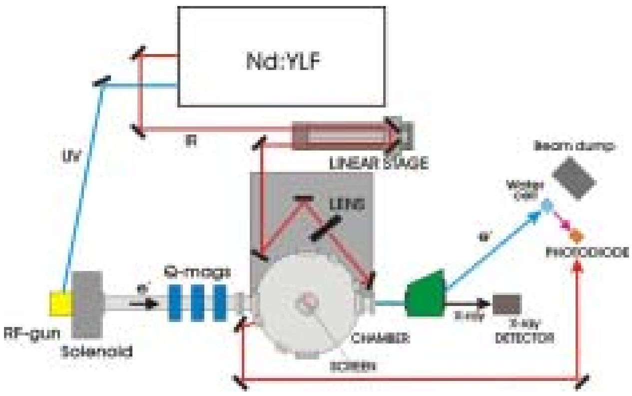

Figure 3: Beam line layout for X-ray generation experiment.

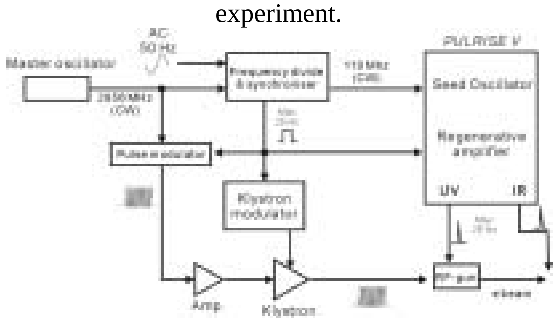

Figure 4: RF and timing diagram for the rf-gun and the laser system

10ps (FWHM) pulsed Nd:YLF (IR:1047nm) laser beam is introduced through the window and focused at the center of the interaction chamber. After interaction, the laser beam pass through the opposite window. A dipole magnet separates the electron beam and the scattered soft X-rays after the interaction point (shown in Figure 3). Soft X-rays are detected using a circular microchannel plate (MCP), which is located 0.6m from interaction point of the electron beam axis. The diameter of MCP sensitive area is 14.5mm correspond to a collection angle θ_s = 12mrad. The quantum detection efficiency of the MCP is about 7 % at 400eV X-ray [8].

3.2 Laser Amplification

Our requirement for the laser light is 40mJ/pulse. However, maximum energy of laser light obtained from our present laser system is about 1mJ/pulse. Therefore a flush lamp pumped 2-passed laser amplification system using Nd:YLF crystal (90mm×60mmϕ) has been designed. The maximum gain obtained from this amplification system is about 1×10^2 at 1kV flushing voltage. Changing the flushing voltage, the optimum laser energy can be arbitrary obtained.

3.3 Preliminary Experiment

Up to now, the electron beam and the laser pulse focusing have been tried at the interaction point. The 5 MeV electron beam with 10ps (FWHM), 1nC were produced by the photo-cathode rf-gun and tried to focused into small beam-spot at the interaction point to get high luminosity. However, we couldn’t be achieved the good focusing of electron beam. It should be limited due to space charge effect and chromatic effect from energy spread. The focused horizontal and vertical electron beam sizes were about 300μm. IR laser pulses were focused into about σ_L=60μm using a optical lens, which is 300mm focal length.

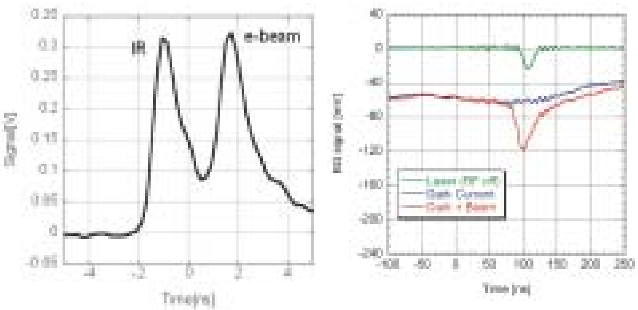

Figure 5: Typical scope-trace of photodiode output shows the electron beam signal (Cherenkov light) and IR laser light (left). Background signal of X-ray detector (right)

Timing adjustment between electron beam and laser pulse has been performed using a remote optical delay line whose active-length is 20cm (correspond to 1.3ns optical delay). To adjust a timing of the scattering, the signals of electron beam and laser pulse have been monitored using a fast photodiode detector, the electron beam signal was Cherenkov radiation, which was generated when the electron beam pass through a water cell at the end of 45 degree beam line (shown in Figure 3). Figure 5(left) shows typical observed photodiode signal of electron beam and laser pulse.

Spatial alignment between electron beam and laser pulse have been done using a screen monitor that is consist of a 100μm thickness phosphor screen and a 300μm thickness aluminium plate with a 600μm diameter hole. Both of the focused electron beam and laser pulse were align to the small hole of the screen monitor.

Background observation has been performed. Figure 5(right) shows the measured background signals under the different conditions. Main background sources were breamsstrahlung of the electron beam and a dark current from rf-gun cavities due to a field emission. They have different time structure, the pulse width of dark current so much longer than breamsstrahlung, therefore we can distinguish these two background noises. We have known that a scattered UV laser light on the cathode surface also make a noise for the X-ray detection, it is shown in Figure 5 (right) as a upper line.

4 SUMMARY

Soft X-ray generation project using the laser Compton scattering has been started at Waseda University. The interaction chamber has been installed to the beam line and it is possible to make three different collision angles between the electron beam and the IR laser light. After the laser amplification system for IR laser light is installed, we will perform the soft X-ray generation experiment.

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