Characteristics of X-rays produced via laser Compton scattering using quasi-monoenergetic electron beam driven by laser-plasma acceleration

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Abstract. X-ray generation via laser Compton scattering has been demonstrated using a quasi-monoenergetic electron beam with a narrow energy spread driven by laser-plasma acceleration. A well-collimated X-ray beam with a divergence angle of approximately 5 mrad is produced. The X-ray photon number is estimated to be $2 \times 10^7$ per pulse. The peak energy of the X-rays is estimated to be 60 keV by a numerical simulation.

1. Introduction
In laser-plasma acceleration, electrons are accelerated by the electric field of a plasma wave driven by an intense laser pulse [1]. The electron pulse duration is extremely short, on the order of 10 fs, because the wavelength of the accelerating field is on the order of 10 $\mu$m. Furthermore, a compact electron accelerator can be realized using a high accelerating field of more than 100 GV/m. Such unique characteristics of laser-plasma acceleration enable us to produce all-optical, compact, femtosecond X-ray sources. Ultrashort X-ray sources have attracted much attention, because of their potential applications in investigating the ultrafast structural dynamics of materials through time-resolved X-ray diffraction and spectroscopy. Various types of ultrashort X-ray sources have been so far developed using a laser-accelerated electron beam [2, 3, 4, 5].

One type of ultrashort X-ray sources is a laser Compton scattering (LCS) X-ray source, which is produced by scattering a femtosecond laser pulse off a high-energy electron beam. LCS X-ray sources can produce a well-collimated, quasi-monochromatic X-ray beam. Several groups have so far reported LCS X-ray generation using a laser-accelerated electron beam [3, 5]. Recently, the generation of high-energy X-rays with a considerably large photon number has been reported. However, because the energy spreads of the electron beams were large, the X-ray energy spreads were also large. For various applications, a quasi-monochromatic X-ray source is desirable. To produce a quasi-monochromatic X-ray source using LCS, a quasi-monoenergetic electron (QME) beam with a narrow energy spread is necessary [6, 7, 8, 9, 10]. In this paper, we report X-ray generation via LCS using a laser-accelerated QME beam.

2. Experimental conditions
Figure 1 shows the experimental setup. The laser pulses for electron acceleration and LCS are referred to as “main pulse” and “colliding pulse”. Both the pulses were horizontally polarized.
The main pulse (800 nm, 700 mJ, 40 fs) was focused onto the edge of a 2-mm-long He gas jet using an \( f/14 \) off-axis parabolic mirror, and the intensity was \( 4.7 \times 10^{18} \) W/cm\(^2\). The colliding pulse (800 nm, 140 mJ, 100 fs) was focused onto the exit of the main pulse from the gas jet using an \( f/6 \) off-axis parabolic mirror, and the intensity was \( 8.8 \times 10^{17} \) W/cm\(^2\). The incident angle of the colliding pulse was 20° with respect to the propagation axis of the main pulse in vacuum referred to as "main laser axis". The plasma electron density was \( 1.5 \times 10^{19} \) cm\(^{-3}\).

LCS X-rays were scattered in the forward direction of electron beam emission. The electron beam was bent by a dipole magnet with a magnetic field of 0.27 T, and was spatially separated from the X-rays. Both the X-rays and electrons were incident on a phosphor screen (DRZ-HGH, Mitsubishi Chemical) through a 115-μm-thick Al filter. The phosphor images of the X-rays and energy-resolved electrons were simultaneously captured with a single shot using a CCD camera. Electrons with energies higher than 30 MeV were observed. The charge of the electron beam was estimated from the calibrated sensitivity of the detection system [11]. The detection system was also sensitive to X-rays with energies from 15 to 150 keV.

3. Experimental results

Figure 2(a) shows the phosphor image, when LCS X-rays were produced. The image on the left side in Fig. 2(a) was the energy-resolved electron image of a QME beam, and the small spot near the main laser axis indicated by a cross was an LCS X-ray image. Figure 2(b) shows the horizontal line profile of the phosphor image at the position, in which the LCS X-ray image was observed. The dashed line indicates the position of the main laser axis. By extrapolating from the saturated intensity of the energy-resolved electron image, the peak energy and charge of the QME beam were estimated to be approximately 60 MeV and 70 pC, respectively. The divergence angles of the X-ray beam estimated from the \( e^{-2} \) intensity radius of the image were 6.2 and 4.2 mrad in the horizontal and vertical directions, respectively. In LCS, the beam divergence angle is given by \( \sim 1/\gamma \), where \( \gamma \) is the Lorentz factor of the electron energy. The divergence angle estimated from the electron energy of 60 MeV (\( \gamma \sim 120 \)) is 8.3 mrad, which is close to the observed divergence angles. This supports that the small spot in Fig. 2(a) is the image of LCS X-rays. The photon energy of the X-rays within the scattering angle of 5 mrad was estimated to range from 30 to 120 keV taking the energy spread of the QME beam between 40 and 70 MeV into account.

The sensitivity to electrons of the detection system using a phosphor screen coupled with a CCD camera has been known [11]. On the other hand, the efficiency of the conversion from the energy deposited in the phosphor layer to the fluorescence for electrons is nearly equal to that for X-rays for a similar type phosphor screen [12]. This indicates that the energies deposited in the phosphor layer determine the sensitivity of the phosphor screen. The sensitivity to X-rays can be deduced from the energies deposited in the phosphor layer on the basis of the sensitivity to electrons. The deposited energies were calculated by the simulation code EGS5 [13]. The sensitivity to X-rays with energies from 30 to 120 keV was approximately one-eighth that to electrons with energies of around 60 MeV. Integrating the counts of the image in Fig. 2(a) yielded the X-ray photon number of \( 2 \times 10^7 \) per pulse. The X-ray photon number per pulse was comparable to those achieved in LCS X-ray sources using rf accelerators [14].

X-ray radiation can be produced by the betatron oscillation of electrons trapped in a plasma wave [2]. The critical energy of betatron radiation X-rays was estimated to be approximately...
Figure 2. (a) Phosphor image and (b) the horizontal line profile of the image, when LCS X-rays were produced. (c) Phosphor image and (d) the horizontal line profile of the image observed without irradiating the colliding pulse.

7 keV for 60 MeV electrons under our experimental conditions. The sensitivity of the detection system to X-rays with energies lower than 7 keV was quite low. As shown in Figs. 2(c)(d), no spot images around the main laser axis were observed without irradiating the colliding pulse. Thus, the spot image in Fig. 2(a) was not the image of betatron radiation X-rays.

4. Numerical simulation results
Characteristics of the LCS X-rays were investigated using the simulation code CAIN [15]. Figure 3 shows (a) the X-ray beam pattern and (b) the spectrum of X-ray photons scattered within an angle of 5 mrad. The peak energy, relative full-width at half-maximum (FWHM) energy spread, charge, normalized emittance, and FWHM bunch length of the QME beam were assumed to be 60 MeV, 35%, 70 pC, 0.8 mm mrad, and 3 μm, respectively. The peak energy, relative FWHM energy spread, and charge were determined by the mean values of QME beam parameters obtained in the another experiment conducted under the same conditions. Other parameters were determined by the particle-in-cell simulation result.

As shown in Fig. 3(a), the X-ray beam pattern was vertically elliptical. In contrast, the observed beam pattern was horizontally elliptical. The reason may be the horizontally elliptical pattern of the QME beam caused by the interaction of the horizontally polarized main pulse with the accelerated electrons [16]. The divergence angles estimated from the $e^{-2}$ intensity radius were 9.3 and 14.1 mrad in the horizontal and vertical directions, respectively. The observed divergence angles were smaller than those of the simulation result. The reason may be the uncertainty in the estimation of the electron energy in the experiment. Errors in the determination of the electron energy were caused by the fluctuation of the incident angle of the electron beam to the magnet. When the emission direction of the QME beam, as well as that of the X-ray beam, was shifted to the left side from the main laser axis as shown in Fig. 2(a), the estimated electron energy was lower than the actual energy. A higher-energy electron beam can produce an X-ray beam with a smaller divergence angle.

The peak energy and photon number of the X-rays scattered within an angle of 5 mrad were 60 keV and $1.8 \times 10^7$, respectively. The photon number was in good agreement with the
experimental result. The energy spread of the X-rays was large, because the energy spread of the QME beam was large. The peak energy of the X-rays was estimated to be 86 keV for 60 MeV electrons. The peak energy of the simulation result was lower than the theoretically predicted value. The X-ray energies were shifted to lower energies because of the increase in the effective mass of electrons caused by the nonlinear interaction with the colliding pulse, the normalized vector potential of which was $\sim 0.6$, close to the relativistic intensity. In the X-ray spectrum, a long tail was also observed in the high energy range. The tail was formed by the higher order harmonics component generated by the nonlinear interaction. The simulation result shows the effect of nonlinear scattering.

5. Summary
We have demonstrated X-ray generation via LCS using a laser-accelerated QME beam. A well-collimated X-ray beam with a divergence angle of approximately 5 mrad was produced. The X-ray photon number was estimated to be $2 \times 10^7$ per pulse. Numerical simulation shows that the peak energy and photon number of the X-rays scattered within an angle of 5 mrad were 60 keV and $1.8 \times 10^7$, respectively. The photon number was in good agreement with the experimental result. The numerical simulation result supports the experimental result.

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