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X-ray generation using an electron beam driven by laser-plasma acceleration
レーザープラズマ加速電子線を用いたX線発生

Eisuke Miura[1)], Koki Maruyama[2)], Ryunosuke. Kuroda[1)], Hiroyuki Toyokawa[1)]
三浦永祐[1)], 丸山昂貴[2)], 黒田隆之助[1)], 豊川弘之[1)]

[1)] *National Institute of Advanced Industrial Science and Technology (AIST)*
Tsukuba Central 2 1-1-1, Umezono, Tsukuba, Ibaraki 305-8568, Japan
[1)] 産業技術総合研究所 〒305-8568 茨城県つくば市梅園1−1−1 中央第2
[2)] *Utsunomiya University*
7-1-2 Yoto Utsunomiya, Tochigi 321-8585, Japan
[2)] 宇都宮大 〒321-8585 栃木県宇都宮市陽東7−1−2

X-ray pulse generation is demonstrated by laser Compton scattering using a laser-accelerated quasi-monoenergetic electron (QME) beam containing 70 pC electrons with an energy of 60 MeV in the monoenergetic peak. 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 2×10^7 per pulse. The peak energy of the X-rays is estimated to be 60 keV by a numerical simulation using the measured characteristics of the QME beam.

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 μm. 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 [2-4].

One type of ultrashort X-ray sources is a laser Compton scattering (LCS) X-ray source [3,5-8], which is produced by scattering a femtosecond laser pulse off a high-energy electron beam. An LCS X-ray source can produce a well-collimated, quasi-monochromatic X-ray beam. To produce a quasi-monochromatic X-ray source desirable for various applications using LCS, a quasi-monoenergetic electron (QME) beam with a narrow energy spread is necessary. In this paper, we report X-ray generation by LCS using a high-charge, laser-accelerated, QME beam.

2. Experimental conditions

A laser pulse (800 nm, 700 mJ, 40 fs) for electron acceleration referred to as the "main pulse" was focused onto the edge of a 2-mm-long He gas jet using an *f*/14 off-axis parabolic mirror. The peak intensity was 4.7×10^{18} W/cm^2. A laser pulse (800 nm, 140 mJ, 100 fs) for LCS referred to as the "colliding pulse" was focused onto the exit of the main pulse from the gas jet using an *f*/6 off-axis parabolic mirror. The peak intensity was 8.8×10^{17} W/cm^2. The incident angle was 20 degree with respect to the propagation axis of the main pulse in vacuum referred to as the "main laser axis". LCS X-rays were scattered in the coaxial 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 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 detection system was also sensitive to X-rays with energies from 15 to 150 keV.

3. Experimental Results and Discussion

Figure 1(a) shows the phosphor image captured with a single shot when LCS X-rays were produced, where the plasma electron density was 1.5×10^{19} cm^{-3}. The image on the left side in Fig. 1(a) was the energy-resolved electron image of a QME beam, and the small spot near the main laser axis shown by the cross was an LCS X-ray image. Figure 1(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 shows 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 size of e^{-2} intensity region 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 γ is the Lorentz factor of the electron energy. The divergence angle estimated from the peak 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 shown in Fig. 1(a) is the image of LCS X-rays. The photon energy of X-rays within the scattering angle of 5 mrad was estimated to range from 25 to 118 keV taking the energy spread of the QME beam between 35 and 70 MeV into account. Integrating the counts with in the e^{-2} intensity region of the image in Fig. 1(a) yielded an X-ray photon number of 2×10^7 per pulse. The X-ray photon number per pulse was comparable to those achieved in LCS X-ray sources using rf accelerators.

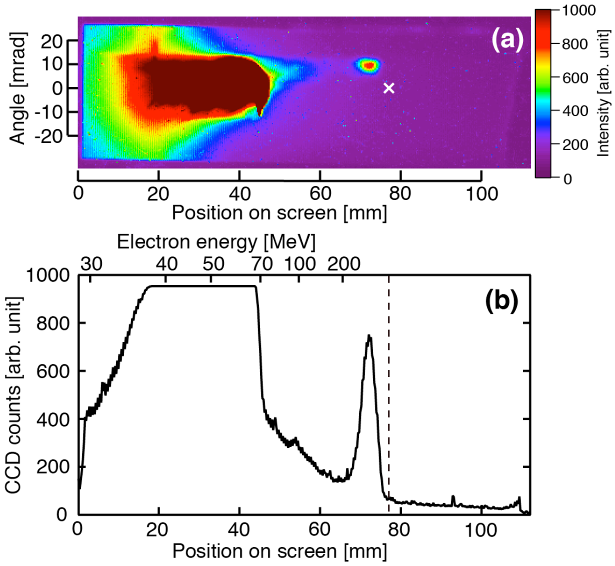

Fig.1. (a) Phosphor image captured with a single shot and (b) the horizontal line profile of the image, when LCS X-rays were produced.

The characteristics of the X-rays were investigated using the simulation code CAIN [9]. Figure 2 shows 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 statistics obtained in the experiment conducted under the same conditions. The other parameters were determined by the particle-in-cell simulation results. The peak energy of the X-rays was 60 keV, and the X-ray photon number was 1.8×10^7. The photon number was in good agreement with the experimental result. The X-ray energy spread remained large, because the electron energy spread of the QME beam was 35%. The peak energy of X-rays was estimated to be 86 keV for 60 MeV electrons under our experimental conditions. The peak energy of the simulation result was lower than the theoretically predicted value. The X-ray energies were shifted to the lower energies because of the increase in the effective mass of electrons caused by the interaction with the colliding pulse, the intensity of which was close to the relativistic intensity. The simulation result suggests the affect of the nonlinear interaction.

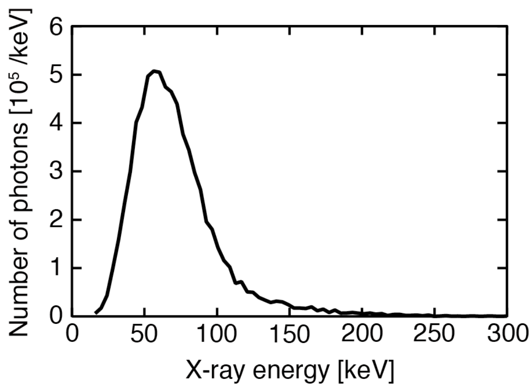

Fig.2. Spectrum of X-ray photons scattered within an angle of 5 mrad calculated by a numerical simulation using the measured characteristics of the QME beam.

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References

[1] T. Tajima, and J. M. Dawson: Phys. Rev. Lett. **43** (1979) 267.

[2] A. Rousse et al.: Phys. Rev. Lett. **93** (2004) 135005.

[3] H. Schwoerer et al.: Phys. Rev. Lett. **96** (2006) 014802.

[4] H. -P. Schlenvoigt et al.: Nature Phys. **4** (2008) 130.

[5] K. T. Phuoc et al.: Nature Photon. **6** (2012) 308.

[6] Y. Mori et al.: Appl. Phys. Express **5** (2012) 056401.

[7] S. Chen et al.: Phys. Rev. Lett. **110** (2013) 155003.

[8] E. Miura et al.: Appl. Phys. Express **7** (2014) 046701.

[9] P. Chen et al.: Nucl. Instrum. Methods A **355** (1995) 107.