SPATIAL PROFILE MEASUREMENT OF FEMTOSECOND LASER - COMPTON X-RAYS

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Abstract

A femtosecond X-ray source was developed by Thomson scattering through interaction between a low-emittance picosecond electron beam and a terawatt femtosecond laser light at 90^o configuration. The observed X-ray intensity with peak energy of 2.3 keV and pulse duration of 270 fs rms was typically 1.4x10^4 photons/pulse. The pulse-to-pulse fluctuation of the X-ray intensity was measured to be 25%. The spatial profile of the X-rays was measured with a technique of X-ray imaging on a phosphor screen using an image-intensified CCD camera. The dependence of the X-ray beam profile on the scattering laser polarization was obtained and compared with theoretical analysis.

1 INTRODUCATION

A short pulse X-ray source is an important tool for studying the dynamics of the materials in the fundamental time scale. The development of femtosecond laser has made it possible to generate such ultrashort X-ray pulses in femtosecond region by means of 90-degree (90^o) Thomson scattering with a relativistic ultrashort-pulse electron beam [1-5]. The X-rays generated from Thomson scattering have other advantages, such as good directional radiation, high brightness, and tunable wavelength.

The intensity of the X-rays generated in Thomson scattering is proportional to the densities of both the electron and laser beam. It is important to tightly focus both the beams in the transverse direction to generate high-brightness X-rays. In addition, the small focused beam size should be required to reduce the interaction time in 90^o Thomson scattering for the generation of femtosecond X-ray pulse [2,3]. However, the focused electron beam size is limited with beam transverse emittance. A low-emittance electron source and a high-quality femtosecond laser are desired in the development of high-brightness femtosecond X-ray source. A laser-driven photocathode RF gun [6,7] is a candidate for the development of X-ray source by Thomson scattering.

2 EXPERIMENTAL ARRANGEMENT

The Thomson femtosecond X-ray source was consisted of a picosecond electron source and a tabletop terawatt femtosecond pulse laser [4]. The laser pulse was temporally synchronized to the electron beam with high precision.

2.1 An Electron Source

The electron beam was produced by a S-band (2856 MHz) photocathode rf gun. The rf gun, which was constructed under the BNL/KEK/SHI collaboration [6], was consisted of two cells: a half cell and a full cell. A copper cathode was located on the side of the half cell. The length of the half cell was designed to be 0.6 times of the full cell length to reduce the beam divergence. At the exit of the rf gun, a single solenoid magnet was mounted for space-charge emittance compensation.

The rf gun was driven by an all solid-state LD-pumped Nd:YAG picosecond laser. The laser was consisted of a passive mode-locked oscillator, a regenerative amplifier, a post amplifier and a frequency converter. The oscillator was phase-locked with a frequency of 119 MHz, the 24th sub-harmonic of the accelerating 2856 MHz rf, by dynamically adjusting the cavity length of the oscillator with a semiconductor saturable absorber mirror controlled by a timing stabilizer. The output of the oscillator was amplified the pulse energy up to 2mJ in the regenerative amplifier and the post amplifier. The amplified laser pulse was frequency quadrupled to 262 nm ultraviolet (UV) light by a pair of frequency conversion crystals. The UV light was injected on the cathode surface at an incident angle of 68^o along the electron beam direction.

The electron beam produced from the rf gun was accelerated with a 70 cm long standing-wave linear accelerator (linac) produced with an alternating-periodic structure. The linac is located at a position of 1.2 m from the cathode. The input rf peak power of both the rf gun and the linac was 7.5 MW that was produced with a 15 MW Klystron. The peak electric fields on axis in the rf gun and the linac were approximately 100 and 25 MV/m, respectively. The repetition rate of the operation was 10 Hz in the experiments. The accelerated electron beam was focused at the interaction point for scattering with the laser light by a triplet quadrupole magnet downstream of the linac. The scattered electrons were bended by a 90^o dipole magnet [4].

2.2 A Terawatt Femtosecond Laser

The terawatt femtosecond laser was consisted of a mode-locked Ti:Sapphire laser oscillator, a pulse stretcher, a regenerative amplifier, a multi-pass post amplifier, and a pulse compressor. The oscillator generated 50 fs pulses at the repetition rate of 119 MHz. The frequency of the laser oscillator was phase-locked with the 119 MHz rf by the same method as the driving laser of the rf gun.

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The 2.5 nJ laser pulses from the oscillator was stretched up to 400 ps, amplified in a regenerative amplifier, and then delivered to the multi-pass post amplifier. The output pulse energy in the regenerative amplifier and the multi-pass amplifier were 10mJ and 270 mJ. The amplified pulses were compressed in the pulse compressor located near the interaction chamber. The compressed pulse duration was typically 100 fs FWHM at about 100 mJ. Both linearly polarized laser beams, as shown in Fig. 1, were used in Thomson scattering with the electron beam and the X-ray spatial profile measurements.

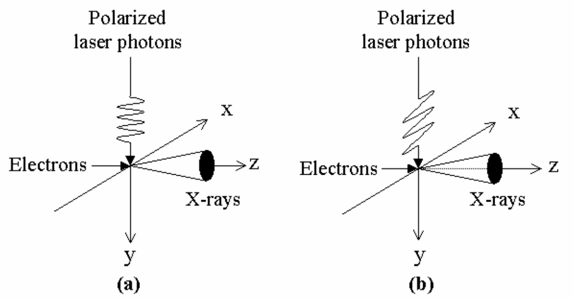

Figure 1: 90° Thomson scatterings in which the electron is travelling in the plane of the laser polarization (a) and perpendicular to the plane of the laser polarization (b).

2.3 Spatial profile Measurement of X-rays

A technique of X-ray imaging on a phosphor screen using an image-intensified charge-coupled device (ICCD) camera (see Fig.2) was used to measure the spatial profile of X-rays. A micro-channel plate (MCP) was installed at the front of the phosphor screen. The distance from the interaction point to the MCP was 2 m. The MCP, which has very low sensitivity for higher energy X-ray and a fast decay time constant in nanosecond region, was chosen to prevent the high energy X-ray background produced by the field emission electrons at the linac and the gun. The diameter of the detector was 77 mm, which corresponded to 19.3 mrad collection angle from the detector. The ICCD camera was synchronized to the electron beam for a single-shot measurement.

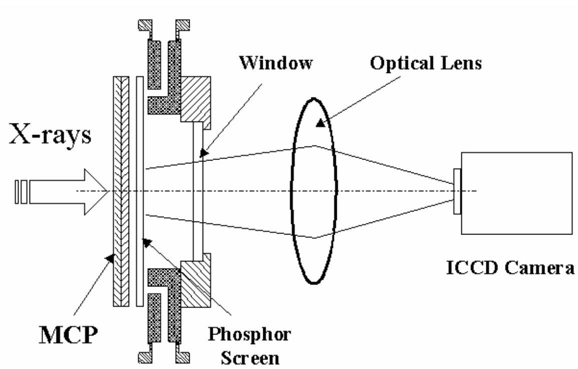

Figure 2: X-ray imaging measurement on a phosphor screen using an image-intensified charge-coupled device (ICCD) camera

The X-ray intensity was measured by another 18-mm-diameter MCP detector which was calibrated precisely with radioisotope sources[4,5].

3 EXPERIMENTAL RESULTS

The characteristics of the electron beam measured in the interaction point are given in Table 1. The UV laser pulse with pulse length of 11 ps FWHM was used to driven the rf gun. The parameters of the femtosecond laser used for the X-ray generation are shown in Table 2. The time jitter between the electron bunch and the femtosecond laser pulse was measured by a streak camera.

Table 1: Characteristics of the electron beam

Beam energy	14 MeV
Energy spread($\Delta E/E$)	0.3 %
Bunch charge	0.5 nC
Pulse duration	3 ps rms
Norm. rms transverse emittance	2 πmm-mrad
Focused beam size	100 μm rms
Fluctuation of beam size	3 μm rms
Pointing stability	6 μm rms

Table 2: Parameters of the laser beam

Wavelength	800 nm
Pulse energy	85 mJ
Pulse duration	100 fs rms
Focused beam size	20 μm rms
Time jitter between the laser pulse and the electron bunch	1.4 ps rms

3.1 Scattered X-ray characteristics

The scattered X-ray intensity was obtained by measuring the yield of X-rays deposited on the MCP detector with background subtraction. The number of X-rays at the interaction point was achieved to be 1.4×10^4 photons/pulse for the given parameters of the electron beam and laser beam. A good linearity between the laser pulse energy and the X-ray intensity was obtained in the experiment [4]. The pulse-to-pulse fluctuation of the X-ray intensity was measured to be 25% rms within the measurement time of about 8 minutes. From the numerical analysis, we found the fluctuation was almost caused by the time jitter of 1.4 ps between the laser pulse and the electron bunch.

The maximum energy and pulse duration of X-rays were calculated to be 2.3 keV and 270 fs rms respectively with the theory of Thomson scattering [2,3] under the experimental conditions (see Tables 1 and 2).

3.2 Spatial profiles of X-rays

The spatial X-ray beam profiles on the phosphor screen using the ICCD camera are given in Figs. 3 and 4 for two scattering geometries of the electron beam travelling parallel to the plane of the laser polarization and perpendicular to the plane of the laser polarization, respectively. The data was observed by integrating 1000 images on the phosphor screen. Background radiation from electron bremsstrahlung has been subtracted with the electron beam on and the laser beam on, but without interaction between the electrons and the laser light.

The ellipticity of the X-ray image is observed in Thomson scattering with the linearly polarized laser light. A larger horizontal than vertical spot size of the X-ray beam is observed when the electron is travelling parallel to the plane of the laser polarization, while the smaller horizontal than vertical spot size of the X-ray beam is observed when the electron is travelling perpendicular to the plane of the laser polarization.

The X-ray profile can be also observed theoretically from the differential cross section of Thomson scattering of linearly polarized laser light with a relativistic electron (β~1) in the electron rest frame,

$$\frac{d\sigma'}{d\Omega'} \cong r_e^2 \sin^2 \Theta = r_e^2 (1-\sin^2\theta' \cos^2\varphi'), \quad (1)$$

where r_e is the classical electron radius and Θ is the angle between the direction of the scattered X-ray and the electric field of the incident laser light. Using Lorentz transformation, Eq. 1 can be rewritten in the laboratory frame as

$$\frac{d\sigma}{d\theta d\varphi} = \left[1 - \frac{1}{\gamma^2}\frac{\sin^2\theta\cos^2\varphi}{(1-\beta\cos\theta)^2}\right]\frac{\sin\theta}{\gamma^2(1-\beta\cos\theta)^2} \quad (2)$$

where γ is the electron energy relative to the electron rest energy. Figures 3(b) and 4(b) show the X-ray spatial distributions obtained from Eq. 2 with the measured data for the cases of the electron travelling parallel to the plane of the laser polarization and the electron travelling perpendicular to the plane of the laser polarization. As shown in figures, the measured X-ray profiles are in good agreement with the theoretical analysis.

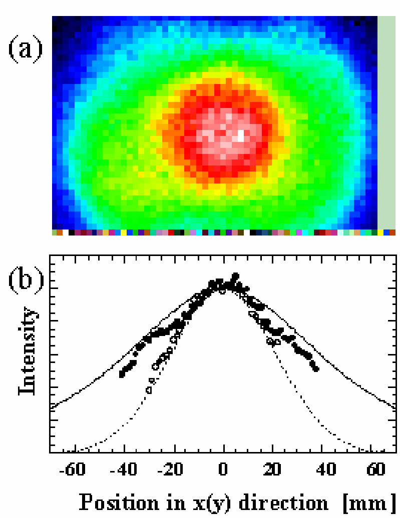

Figure 3: (a) Image of the spatial profile of X-rays on the phosphor screen obtained with the P-polarized laser (see Fig. 1a). (b) horizontal (dots) and vertical (circles) line profiles with the theoretical results (solid and dotted curves).

4 CONCLUSION

A femtosecond X-ray source was demonstrated thought 90° Thomson scattering between a picosecond electron beam and a terawatt femtosecond laser. The X-ray intensity was obtained to be $1.4\text{x}10^4$ photons/pulse with a peak energy of 2.3 keV and a pulse duration of 270 fs rms. The fluctuation of the X-ray intensity was measured to be 25% rms for pulse-to-pulse. The spatial profile of the X-rays was measured as a function of the scattering laser polarization, and compared with theoretical analysis.

In order to utilize this X-ray source in practical applications, we plan to increase the X-ray energy up to 15 keV by accelerating the electron energy up to 40 MeV in the next step. A 1 J femtosecond laser is planed to increase the X-ray intensity. The stabilities of the electron and laser beams will be also improved to obtain a more stable femtosecond X-ray source.

This work was performed under the management of a technological association, the Femtosecond Technology Research Association (FESTA), supported by the New Energy and Industrial Technology Development Organization (NEDO).

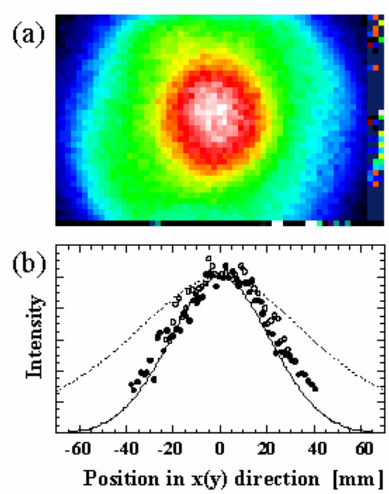

Figure 4: (a) Image of the spatial profile of X-rays on the phosphor screen obtained with the S-polarized laser (see Fig. 1b). (b) horizontal (dots) and vertical (circles) line profiles with the theoretical results (solid and dotted curves)

5 REFERENCES

[1] R. W. Schoenlein, et al., Science 274, (1996) 236
[2] K.-J. Kim, S. Chattopadhyay and C.V. Shank, Nucl. Instr. Meth. A**341** (2000) 351.
[3] J. Yang, M. Washio, A. Endo and T. Hori, Nucl. Instr. & Meth. A**428**, (1999) 556.
[4] J. Yang et. al., Proc. of APAC'2001, Beijing, 271.
[5] M. Yorozu, et al., Appl. Phys. B **47**, (2002) 327.
[6] F. Sakai et al., Jpn. J. Appl. Phys. **41**, (2002) 1589.
[7] J. Yang et al., Rev. Sci. Instr. **73**, (2002) 1752.