DEVELOPMENT OF HIGH-BRIGHTNESS FEMTOSECOND X-RAY SOURCE

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Abstract

A high-brightness femtosecond X-ray source, based on Thomson scattering of a low-emittance electron beam with a femtosecond pulse laser at a 90-degree interaction configuration, has been developed and will be expected for the study of ultra-fast structural dynamics of materials. The electron beam was generated by a laser-driven photocathode RF gun and accelerated up to 14MeV with a linac. A 270fs pulse X-rays with a peak energy of 2.3keV were achieved experimentally in the interaction of a 3ps electron bunch with a 100fs Ti:Sapphire laser light. The intensity of the X-rays was obtained to be $1.4x10^4$/pulse under the experimental conditions of a 0.5nC electron bunch and a 100mJ laser pulse energy. The stability of the X-ray intensity was obtained to be 25%(rms).

1 INTRODUCTION

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 made it possible to study short time reactions in the femtosecond region. However, this optical probe is limited to studying extended electronic levels in solids, due to the low photon energy. A hard X-ray beam is required for studying the structure of solids through their interactions with core electronic levels in atoms. A femtosecond X-ray pulses can be used to observe structural dynamics on femtosecond time scale by utilizing various techniques, such as X-ray diffraction and extended X-ray absorption fine structure (EXAFS). The short pulse X-ray is also useful for industrial applications such as non-destructive inspection of high-speed rotating materials, and for medical imaging applications.

A hard femtosecond X-ray pulse was generated through Thomson scattering of a relativistic electron beam with a femtosecond laser light at a 90-degree interaction configuration[1,2]. The X-rays generated from Thomson scattering have some advantages, such as good directional radiation, high brightness, tunable wavelength and a short pulse in the picosecond and femtosecond regions.

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 focused 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 the 90-degree Thomson scattering for the generation of femtosecond X-ray pulse[3,4]. However, the focused beam size is limited with the 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.

We have generated a low-emittance electron beam by a laser-driven photocathode RF gun, and developed a stable femtosecond tera-watt Ti:Sapphire laser. A 270fs pulse X-rays with a peak energy of 2.3keV and an intensity of 10^4/pulse were generated successfully by using the electron beam and the femtosecond laser.

2 EXPERIMENTAL SETUP

The whole system is shown in Fig. 1. Electron beam is generated by a 1.6-cell S-band (2856MHz) photocathode RF gun driven by a picosecond UV laser[5]. The

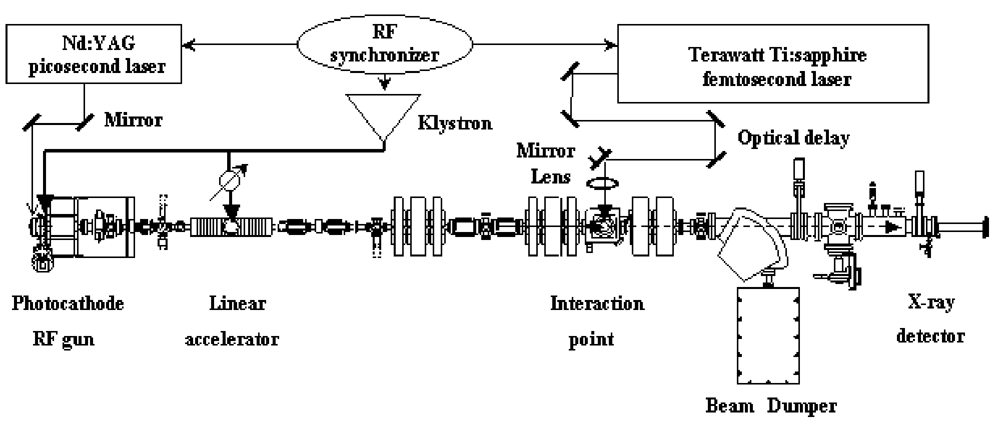

Fig. 1 A femtosecond X-ray source

electrons are accelerated with a linear accelerator (linac) up to 14MeV, and then focused with magnetic focusing lens at the interaction point. A Ti:Sapphire femtosecond tera-watt laser is used as the light source for the X-ray generation. The laser light interacts with the electron beam at the 90-degrees configuration. The electrons after the interaction with the laser light are bent with a bending magnet and damped at the lead block to prevent any X-ray background caused by electron bombardment of the duct wall.

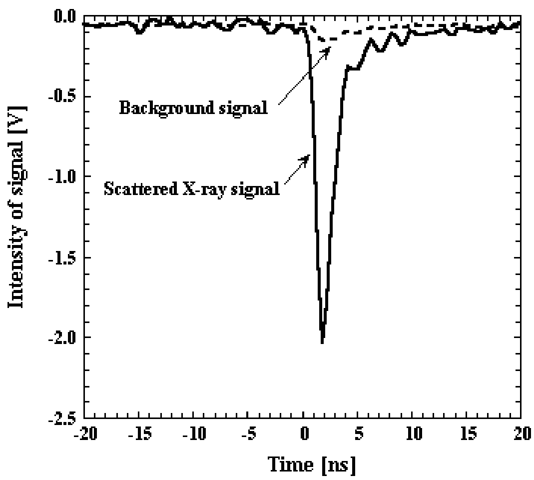

Fig. 2 The ouput of MCP signals

The 1.6 cell photocathode RF gun for high duty operation was developed by the BNL/KEK/Sumitomo collaboration[6]. An LD pumped Nd:YAG UV laser was developed to drive the RF gun[7]. This laser consists of a passive mode-locked oscillator with a semiconductor saturable absorber mirror (SESAM), a regenerative amplifier and a multi-pass post amplifier, and a frequency conversion part. The oscillator operates at a repetition rate of 119 MHz, the 24^{th} sub-harmonic of the accelerating 2856 MHz RF. A timing stabilizer minimized the timing jitter of the oscillator by adjusting the laser cavity length. The timing jitter between the reference RF signal and the output of the oscillator was controlled to within 0.5ps. The UV (266nm) pulse energy was more than 200μJ. The fluctuation of the UV laser pulse energy was measured to be 3-5%(rms). The cathode is made of copper for a long lifetime. The quantum efficiency of a cathode was achieved to be $1.5x10^{-4}$. with the maximum electron charge of more than 2nC/pulse. In the X-ray generation, the bunch charge of 0.5nC was used for a low normalized rms transverse emittance of 2 πmm-mrad. The energy dispersion (δE/E) was 0.1% (rms.) at 14MeV.

The 1 tera-watt femtosecond Ti:Sapphire laser system was developed [8] as a scattering light source. The mode-locked Ti:Sapphire laser oscillator generated 50 fs pulses at the repetition rate of 119MHz. The frequency of the laser oscillation was controlled by the same method as the drive laser for the gun. The 2.5nJ laser pulses from the oscillator were stretched in a pulse stretcher up to 400ps, amplified in a regenerative amplifier, and then delivered to a multi-pass post amplifier. The output pulse energy in the regenerative amplifier and the multi-pass amplifier were 10mJ and 270mJ. The amplified pulses were compressed in a pulse compressor located near the interaction chamber. The pulse compressor consisted of a pair of gratings, with one grating installed in vacuum. The compressed pulse energy and the pulse duration were typically 100mJ and 100fs (FWHM). The time jitter between the electron bunch and the femtosecond laser pulse was measured within 1.4ps(rms) by a streak camera.

A micro-channel plate (MCP) used as an X-ray detector was located 2m from the interaction point. 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 18mm, which corresponded to 4.5mrad collection angle from the detector. The calibrated gain of the MCP was 2.6pC/photoelectron. The quantum efficiency of the detector was also calibrated with radioisotope sources. The detector efficiency was found to be 5% and 8% for X-rays with 4.6keV and 2.3keV energy, respectively [9],[10].

3 RESULTS AND DISCUSSION

The electron and the laser beam parameters in the head-on and 90-degree configurations are shown in Table I. The electron beam size at the interaction point was measured with a 100 μm thick phosphor screen and a CCD camera. The laser beam size was also measured at the screen. The charge of the electron bunch was measured by a current transformer with a fast response time. The laser pulse duration was measured by the standard correlation method. The pulse duration of the electron bunch was measured by a technique of temporal scan in the 90-degree Thomson scattering, which is monitoring the X-ray yield with changing the time delay between the electron bunch and the femtosecond laser pulse.

Figure 2 shows the MCP signals: (a) the scattering X-

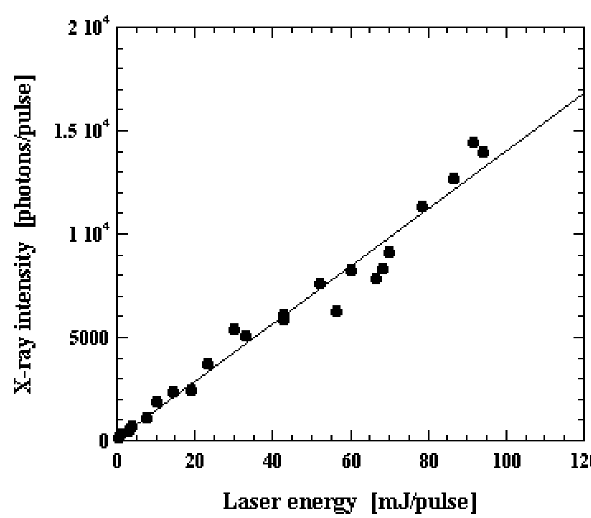

Fig. 3 The linearity of the X-ray intensity with the laser pulse energy.

ray signal and (b) the background signal. The yield of X-rays deposited on the MCP detector was obtained from the gain and the quantum efficiency of the detector as 280photons/pulse. The number of X-rays at the interaction point was estimated to be 1.4×10^4 photons/pulse from the collection angle. A relation between the laser energy and the number of the scattering X-ray photons was measured, as shown in Fig. 3. A good linearity is given in the experiment.

The energy of the scattering X-ray photons was calculated to be 2.3 keV with the theory of Thomson scattering[4,5]. The pulse duration of X-rays was estimated to be 270fs(rms) under the electron beam and the laser parameters given in Table I.

We also measured the pulse-to-pulse fluctuation of the X-ray intensity, as given in Fig. 4. The number of X-ray pulses measured is 5000, which was obtained in about 8 min. As shown in Fig. 4, a stable X-ray beam was achieved in the experiment. The fluctuation of the X-ray intensity was obtained to be 25%(rms) given as Fig. 4(b). From the analysis, we found that the fluctuation is almost caused by the time jitter of 1.4ps between the electron bunch and the femtosecond laser pulse. Other instabilities, such as electron charge, laser energy, beam size and beam pointing instability, cause 10% fluctuation of the X-ray intensity[?].

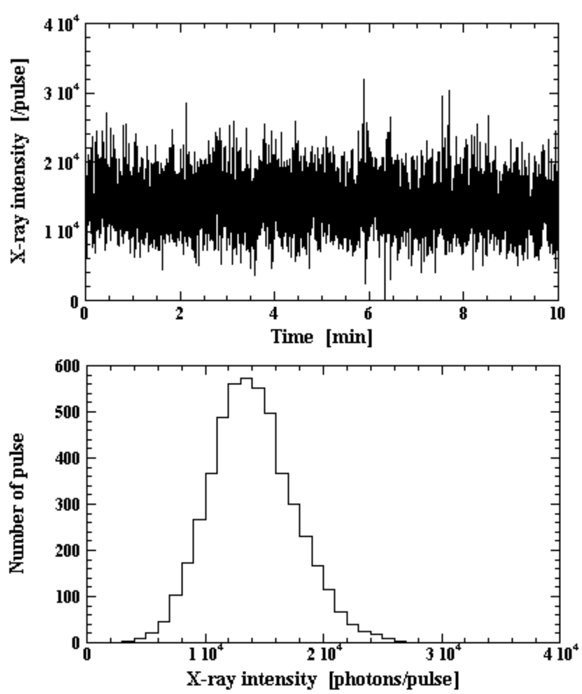

Fig. 4 The pulse-to-pulse fluctuation of the X-ray intensity.

4 CONCLUSION

The generation of femtosecond X-ray pulses was demonstrated through Thomson scattering in a 90-degree collision between a low-emittance relativistic electron beam and a tera-watt femtosecond laser. The number of X-ray photons generated at an interaction points was obtained to be 1.4×10^4. The rms pulse duration of the X-rays with a peak energy of 2.3keV was estimated with the measured beam parameters of the electron and the laser to be 270 fs(rms). The fluctuation of the X-ray intensity was measured to be 25%(rms).

We plan to increase the X-ray energy from a few keV to 30keV by increasing the electron energy up to 40keV to utilize this X-ray source in practical applications, e.g. non-destructive inspection of defects in high-speed rotational metals and the medical imaging. A 1J femtosecond laser is also planed for intense X-rays in a couple of years. We will improve the stabilities of the electron and laser beams to obtain a more stable femtosecond X-ray source.

5 ACKNOWLEDGEMENT

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Table 1: Parameters of the electron and the laser beams

Picosecond electron beam	
Energy(MeV)	14
Energy spread (ΔE/E: %)	0.25
Charge(nC/pulse)	0.5
Beam size(μm:rms)	100
Pulse duration(ps:rms)	3
Pointing stability(μm at 100μm)	6
Fluctuation of beam size(μm:rms)	3
Femtosecond laser pulse	
Wavelength(nm)	800
Pulse energy (mJ/pulse)	85
Pulse duration (fs: rms)	100
Beam size (μm:rms)	20
Time jitter between the laser pulse and the electron bunch(ps:rms)	<1.4

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