A Short Pulse X-Ray Generation via Laser Thomson Scattering on Relativistic Electron Beams

Hideyuki Kotaki*, Kazuhisa Nakajima*,**, Masaki Kando*, Hyeyoung Ahn*, Hideki Dewa*, Syuji Kondoh*, Fumio Sakai*, Takahiro Watanabe***, Toru Ueda***, Kenichi Kinoshita***, Koji Yoshii***, Hiroshi Nakanishi**, Atsushi Ogata**, Mitsuru Uesaka***
*JAERI, Tokai, Ibaraki, Japan 319-11,
**KEK, Tsukuba, Ibaraki, Japan 305,
***NERL, The University of Tokyo, Tokai, Ibaraki, Japan 319-11

Abstract

Short pulsed X-rays were experimentally generated by 90° Thomson scatterings of 2 TW, 90 fs laser pulses by 17 MeV electron beams. Synchronization between the laser pulses and electron beams were achieved within a few ps. A 100 fs X-ray pulse will be generated via backward Thomson scatterings from a 100 fs electron bunch made by a bunch compression chicane. A high peak power, high brightness, high repetitive laser synchrotron radiation source consisting of counter-colliding laser and electron storage rings is proposed.

1 Introduction

A compact, narrow bandwidth, ultrashort pulses of hard X-rays have basic and industrial applications in a number of fields, such as solid-state physics, material, chemical, biological and medical sciences. An ultrashort pulse X-ray source will allow measurements of time resolve atomic motion providing important information about the material properties, chemical and biological reactions on ultrafast time scales. The present high-brightness hard X-ray sources have been developed as third generation synchrotron light sources based on large-scale high energy electron storage rings and magnetic undulators. Recently availability of compact terawatt lasers referred to as table-top-terawatt (T^3) lasers based on chirped pulse amplification arouses a great interest in the use of lasers as undulators of which a period is $\sim 10^4$ shorter than the conventional undulator. This feature of laser undulators allows the use of $\sim$ 100 times less energetic electrons to generate X-rays of a particular wavelength. The laser undulator concept using T^3 lasers makes it possible to construct an attractive compact synchrotron radiation source which has been proposed as a laser synchrotron radiation source (LSRS)[1].

In order to generate an ultrashort X-ray pulse, we attempted 90° Thomson scattering experiments, where a femtosecond laser pulse interacts with a relativistic electron beam at 90° [2]. In this configuration the X-ray pulse length is determined by the transit time of the laser pulse across the electron beam waist as long as the laser pulse length is much shorter than the electron bunch length. It is, however, essential to achieve an exact timing between the laser pulse and the electron pulse. Experiments were carried out by using a T^3 laser delivering laser pulses of 90 fs duration with the peak power of 2 TW and a 17 MeV electron beam of 10 ps bunch length produced from the RF linac synchronized with laser pulses at the repetition rate of 10 Hz.

If the electron pulse duration is as short as a femtosecond, head-on collisions of laser pulses with the electron beam should generate femtosecond X-ray pulses through backscattering. The head-on configuration can produce twice higher energy photons than the 90° configuration as well as the higher photon intensity. In this scheme a difficulty in timing between laser and electron pulses can be relaxed as long as a spatial overlapping of two beams can be accomplished. In order to test the backward Thomson scattering to generate femtosecond X-ray pulses, we prepare the picosecond photocathode injector and the bunch compression chicane in the electron linac.

As an example of a practical high-brightness quasi-monochromatic, high repetitive ultrashort hard X-ray source, we propose a compact synchrotron radiation source consisting of counter-colliding laser and electron storage rings where the compressor and the stretcher for both beams are installed. A conceptual design is discussed for providing high peak power as well as high average power comparable to the present conventional synchrotron light source.

2 X-ray generation via Thomson scattering

When a laser beam interacts with an electron beam at an angle ϕ, Thomson scatterings of relativistic electrons in the laser undulator field generate frequency up-shifted radiation with the peak frequency given by

$$\omega_X = \frac{2\gamma^2(1-\cos\phi)}{1+a_0^2/2}\omega_0, \qquad (1)$$

where γ is the Lorentz factor of the electrons, ω_0 the incident laser frequency and a_0 the undulator strength or the normalized vector potential of the laser field given by $a_0 \sim 0.85\times10^{-9}I^{1/2}[\mathrm{W/cm^2}]\lambda_0[\mu\mathrm{m}]$ for the peak intensity I in units of W/cm^2, the laser wavelength $\lambda_0 = 2\pi c/\omega_0$ in units of μm. For the $\phi = 90°$ configuration, the maximum radiation photon energy is

$$E_X[\mathrm{keV}] = \hbar\omega_X = 9.5\times10^{-3}\frac{E_b^2[\mathrm{MeV}]}{\lambda_0[\mu\mathrm{m}](1+a_0^2/2)}, \qquad (2)$$

where E_b is the electron beam energy. The radiation wavelength is $\lambda_X[\mathring{A}] = 12.4/E_X[\mathrm{keV}]$. In the head-on configuration with $\phi = 180°$, the maximum photon energy turns out to be twice as high as the $\phi = 90°$ configuration. The angular distribution of radiation with the spectrum $\lambda \geq \lambda_X$ is within a cone of half angle, $\theta = (1/\gamma)\sqrt{(\lambda-\lambda_X)/\lambda_X}$.

2.1 90° *Thomson scattering*

Assuming the Gaussian temporal and spatial distributions of both the electron and laser beam with the transverse and longitudinal beam sizes of σ_x and σ_z and the laser transverse and longitudinal laser beam sizes of σ_w and σ_L, the rms pulse length of the X-ray radiation is obtained from

$$\sigma_X = \frac{\sigma_z\sqrt{\sigma_x^2 + \sigma_w^2 + \sigma_L^2}}{\sqrt{\sigma_z^2 + \sigma_x^2 + \sigma_w^2 + \sigma_L^2}}. \qquad (3)$$

The number of photons per pulse within the spectral width $\Delta\omega/\omega$ is given by[2]

$$\Delta n = \frac{113 N_e J \lambda_0}{\sqrt{(\sigma_x^2 + \sigma_w^2)(\sigma_z^2 + \sigma_x^2 + \sigma_w^2 + \sigma_L^2)}}\frac{\Delta\omega}{\omega}, \qquad (4)$$

where N_e is the total number of electrons per bunch, J the laser pulse energy in Joules, and λ_0 and the beam sizes are measured in μm.

2.2 Backward Thomson scattering

In the head-on configuration x-rays are generated toward the direction of the electron beam propagation. It turns out that the x-ray pulse length is determined primarily by the electron pulse duration, i.e. $\sigma_X = \sigma_z$. The number of photons per pulse within the spectral width $\Delta\omega/\omega$ is obtained from[1]

$$\Delta n = 4 \times 10^3 \frac{N_e J}{Z_R[\mu\text{m}]}\frac{\Delta\omega}{\omega}, \qquad (5)$$

where $Z_R = \pi r_0^2/\lambda_0$ is the Rayleigh length, r_0 the spot radius of the Gaussian laser profile and $r_0 \sim r_b$ is assumed with the electron beam radius r_b.

3 Experiments at 17 MeV Linac

Experiments of X-ray generation through Thomson scattering are made by the use of the 17 MeV electron linac and the T^3 laser system[3]. The Ti:sapphire T^3 laser system based on the chirped-pulse amplification at λ_0 = 790 nm produces output pulses compressed by a grating compressor to 90 fs with an energy of > 200 mJ corresponding to a peak power of > 2 TW at the repetition rate of 10 Hz. The electron beam is delivered from the 2856 MHz RF linac to produce a 17 MeV single bunch beam with a 10 ps FWHM pulse duration at the repetition rate of 10 Hz. An electron pulse is synchronized to laser pulses with the phase locked control of the mode-locked oscillator. The phase locked loop maintains synchronization of the oscillator repetition period (79.33 MHz) with every 36th RF period of the linac (2856 MHz). We measured a timing jitter between the laser pulse and Cherenkov radiation from the electron beam with the streak camera with a time resolution of 200 fs. Synchronization between two pulses was achieved within the rms jitter of 3.7 ps.

The setup for the 90° Thomson scattering experiment is shown in Fig. 1.

Laser pulses were focused with f/10 off-axis parabolic (OAP) mirror with a focal length of 480 mm. The electron beam from the linac is focused by a permanent quadrupole (PMQ) triplet in the chamber. Since the electron beam spot size was 480 μm, the X-ray pulse duration of 1.6 ps was expected. The linac was separated with a 50μm thick titanium window from the interaction chamber to maintain ultrahigh vacuum in the linac. The incident electron beam was swept off with the α magnet at a bending angle of 270°. The X-ray radiation was detected by a scintillator with the 1×6 cm^2 sensitive area to be coupled to the photomultiplier tube. Plenty of the bremsstrahlung background was generated from the titanium window and the upstream beam line. In order to subtract the background signal, two sets of X-ray signals were taken with laser pulses and without them as the background. The signal was averaged over 500 to1000 shots to reduce a signal fluctuation. A net signal height proportional to the X-ray flux was obtained from subtracting the background signal from the signals with interaction. Fig. 2 shows the net X-ray signals observed as the timing between laser and electron pulses was scanned.

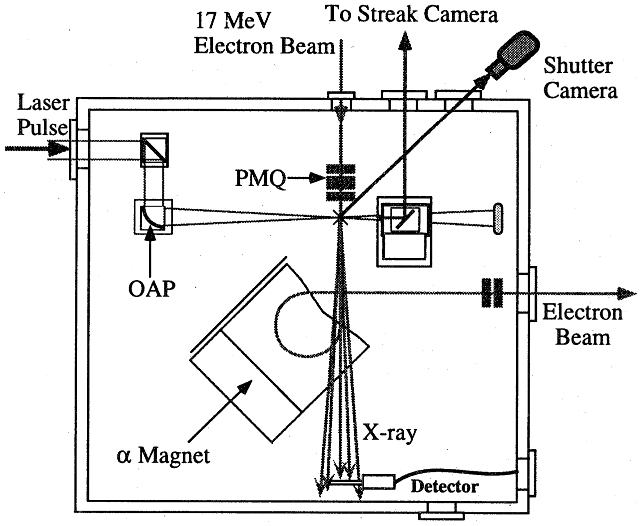

Fig. 1 The experimental setup for 90° Thomson scattering.

In order to test ultrashort pulse X-ray generation by the backward Thomson scattering in the head-on configuration, the bunch compression chicane. is installed in the beam line following the linac to produce the pulse duration of ~ 100 fs. The present thermionic electron gun is replaced by the photocathode RF gun. which can provide a small normalized emittance of ~ 1πmm-mrad and the electron pulse duration of 1 ps. Estimates of experimental parameters are summarized in Table 1.

4 Laser Synchrotron Radiation

Consider that LSRS is composed of a compact electron storage ring and a storage ring of laser pulses with the low gain amplifier to compensate the power loss due to X-ray radiation. Ultrashort intense X-ray pulses can be generated by the head-on interaction between ultrashort electron and laser pulses made through the pulse compressors for both beams at the interaction region. After passing through the interaction, both pulses are stretched in the other section of the ring to avoid beam instabilities or damages in the optical components. This system will allow both a high peak power and a high average power operations of LSRS in a com-

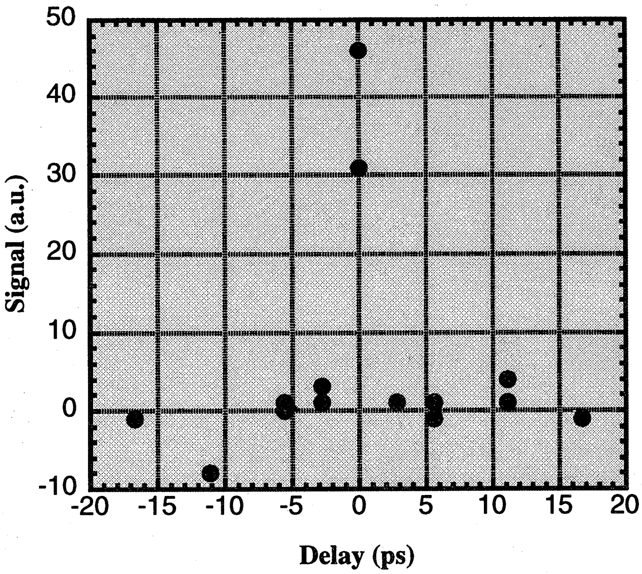

Fig. 2 X-ray signals observed as a function of the time delay between laser and electron pulses.

pact size. Table 2 summarizes design parameters of LSRS performance[1].

5 Conclusion

A short pulse X-ray generation was observed by the 90° Thomson scattering of 2 TW, 90 fs laser pulses from the 17 MeV electron beam. A femtosecond X-ray pulse is efficiently generated via the backward Thomson scattering with the electron pulse compression. A compact, high peak power, high brightness laser synchrotron radiation source is proposed to provide attractive features comparable to a large storage ring based synchrotron light source.

References

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[3] K. Nakajima, Phys. Plasmas, **3**, 2169 (1996).

Table 1
Parameters of X-ray generation experiments

Laser beam	
Wavelength	790 nm
Peak power	2 TW
Pulse energy	0.2 J
Pulse duration	90 fs
Focal spot radius	150μm
Electron beam	
Energy	17 MeV ($\gamma = 33$)
Pulse duration	100 fs
Charge/pulse	1 nC
Beam radius	150μm
X-ray pulse	
Photon energy	7 keV ($\lambda_X = 1.8\mathring{A}$)
Pulse duration	100 fs
Number of photons	$5 \times 10^7 (\Delta\omega/\omega = 0.1)$
Collection angle (2θ)	2×9 mrad

Table 2
A design of laser synchrotron radiation

Laser pulse parameters	
Wavelength	0.8μm
Pulse energy	1 J
Peak power	10 TW
Pulse duration	100 fs
Spot radius	50μm
Rayleigh length	1 cm
Repetition rate	10 MHz
Electron pulse parameters	
Energy	150 MeV
Peak current	100 kA
Average current	100 mA
Pulse duration	100 fs
Beam radius	50μm
Revolution frequency	10 MHz
X-ray pulse parameters	
Photon energy	530 keV max.
Pulse duration	100 fs
Peak photon flux	2.5×10^{23} photons/s
Peak brightness†	2×10^{20}
Peak radiation power	3.6 GW
Average photon flux	2.5×10^{17} photons/s
Average brightness†	2×10^{14}

† photons/s mm^2 mrad^2 0.1 % BW