A SHORT PULSE X-RAY GENERATION VIA THOMSON
SCATTERING OF ULTRASHORT LASER PULSES BY
RELATIVISTIC ELECTRON BEAMS

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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 consist-
ing 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 mate-
rial properties, chemical and biological reactions on ul-
trafast time scales. The present high-brightness hard X-
ray sources have been developed as third generation syn-
chrotron 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 (T³) lasers based on chirped pulse amplifica-
tion arouses a great interest in the use of lasers as undula-
tors of which a period is ~ 10⁴ shorter than the conven-
tional undulator. This feature of laser undulators allows
the use of ~ 100 times less energetic electrons to gener-
ate X-rays of a particular wavelength. The laser undula-
tor concept using T³ 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 at-
tempted 90° Thomson scattering experiments, where a
femtosecond laser pulse interacts with a relativistic elec-
tron 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 T³ 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 femtosec-
ond, 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 dif-
ficulty 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 pre-
pare 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 radia-
tion with the peak frequency given by

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

where γ is the Lorentz factor of the electrons, ω₀ the
incident laser frequency and a₀ the undulator strength or the
normalized vector potential of the laser field given by a₀ ~
0.85 × 10⁻⁹ I₁/²[W/cm²]λ₀[μm] for the peak intensity I
in units of W/cm², the laser wavelength λ₀ = 2πc/ω₀ in
units of $\mu$m. For the $\phi = 90^\circ$ configuration, the maximum radiation photon energy is

$$E_X [\text{keV}] = \hbar \omega_X = 9.5 \times 10^{-3} \frac{E_b^2 [\text{MeV}]}{\lambda_0 [\mu m] (1 + a_0^2/2)}.$$  

(2)

where $E_b$ is the electron beam energy. The radiation wavelength is $\lambda_X [\AA] = 12.4/E_X [\text{keV}]$. In the head-on configuration with $\phi = 180^\circ$, the maximum photon energy turns out to be twice as high as the $\phi = 90^\circ$ 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 $90^\circ$ Thomson scattering

Assuming the Gaussian temporal and spatial distributions of both the electron and laser beam with the transverse and longitudinal beam sizes of $\sigma_x$ and $\sigma_z$ and the laser transverse and longitudinal laser beam sizes of $\sigma_w$ and $\sigma_L$, the rms pulse length of the X-ray radiation is obtained from

$$\sigma_X = \frac{a \sqrt{\sigma_x^2 + \sigma_w^2 + \sigma_L^2}}{\sqrt{\sigma_x^2 + \sigma_w^2 + \sigma_L^2}}.$$  

(3)

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

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

(4)

where $N_e$ is the total number of electrons per bunch, $J$ is the laser pulse energy in Joules, and $\lambda_0$ and the beam sizes are measured in $\mu$m.

### 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. $\sigma_X = \sigma_x$. The number of photons per pulse within the spectral width $\Delta \omega/\omega$ is obtained from[1]

$$\Delta n = 4 \times 10^{-3} \frac{N_e J}{Z_R/\lambda_0} \frac{\Delta \omega}{\omega},$$  

(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 $\lambda_0 = 790$ 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 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 $90^\circ$ Thomson scattering experiment is shown in Fig. 1.

![Figure 1: The experimental setup for $90^\circ$ Thomson scattering.](image)

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 $\mu$m, the X-ray pulse duration of 1.6 ps was expected. The linac was separated with a 50$\mu$m thick titanium window from the interaction chamber to maintain ultrahigh vacuum in the linac. The incident electron beam was swept off with the $\alpha$ magnet at a bending angle of 270$^\circ$. The X-ray radiation was detected by a scintillator with the $1 \times 6$ 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 to 1000 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.

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

following the linac to produce the pulse duration of \( \sim 100 \) fs. The present thermionic electron gun is replaced by the photocathode RF gun which can provide a small normalized emittance of \( \sim 1\text{πmm-mrad} \) and the electron pulse duration of 1 ps. Estimates of experimental parameters are summarized in Table 1.

Table 1: Parameters of X-ray generation experiments.

<table>
<thead>
<tr>
<th>Laser beam</th>
<th>Electron beam</th>
<th>X-ray pulse</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength 790 nm</td>
<td>Energy 17 MeV ((\gamma = 33))</td>
<td>Photon energy 7 keV ((\lambda_{X} = 1.8\text{Å}))</td>
</tr>
<tr>
<td>Peak power 2 TW</td>
<td>Pulse duration 100 fs</td>
<td>Pulse duration 100 fs</td>
</tr>
<tr>
<td>Pulse energy 0.2 J</td>
<td>Charge/pulse 1 nC</td>
<td>Number of photons (5 \times 10^7(\Delta\omega/\omega = 0.1))</td>
</tr>
<tr>
<td>Pulse duration 90 fs</td>
<td>Beam radius 50(\mu)m</td>
<td>Collection angle ((2\theta)) (2 \times 9\text{ mrad})</td>
</tr>
</tbody>
</table>

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

Table 2: A design of laser synchrotron radiation.

<table>
<thead>
<tr>
<th>Laser pulse parameters</th>
<th>Electron pulse parameters</th>
<th>X-ray pulse parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength 0.8(\mu)m</td>
<td>Energy 150 MeV</td>
<td>Photon energy 530 keV max.</td>
</tr>
<tr>
<td>Pulse energy 1 J</td>
<td>Peak current 100 kA</td>
<td>Pulse duration 100 fs</td>
</tr>
<tr>
<td>Peak power 10 TW</td>
<td>Average current 100 mA</td>
<td>Peak photon flux (2.5 \times 10^{23}) photons/s</td>
</tr>
<tr>
<td>Pulse duration 100 fs</td>
<td>Pulse duration 100 fs</td>
<td>Peak brightness(\dagger) (2 \times 10^{20})</td>
</tr>
<tr>
<td>Spot radius 50(\mu)m</td>
<td>Beam radius 50(\mu)m</td>
<td>Peak radiation power 3.6 GW</td>
</tr>
<tr>
<td>Rayleigh length 1 cm</td>
<td>Revolution frequency 10 MHz</td>
<td>Average photon flux (2.5 \times 10^{17}) photons/s</td>
</tr>
<tr>
<td>Repetition rate 10 MHz</td>
<td></td>
<td>Average brightness(\dagger) (2 \times 10^{14})</td>
</tr>
</tbody>
</table>

\(\dagger\) photons/s mm\(^2\) mrad\(^2\) 0.1 % BW

5 CONCLUSION

A short pulse X-ray generation was observed by the 90\(^{\circ}\) 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.

6 REFERENCES