Small-angle Thomson scattering of ultrafast laser pulses
for bright, sub-100-fs X-ray radiation

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Abstract

We propose a scheme for bright sub-100-femtosecond X-ray radiation generation using small-angle Thomson scattering. Coupling high-brightness electron bunches with high-power ultrafast laser pulses, radiation with photon energies between 8- to 40-keV can be generated with pulse duration comparable to that of the incoming laser pulse with peak spectral brightness close to those of the third-generation synchrotron light sources of $\sim 10^{20}$ photons s$^{-1}$ mm$^{-2}$ mrad$^{-2}$ per 10$^{-3}$ bandwidth.

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I. INTRODUCTION

Understanding structural dynamics in physics, chemistry, and biological science at the fundamental time scale of atomic motion (below ~100 fs) needs ultrafast probes like ultrashort X-ray pulses and electron bunches. Currently, although there are several ways one can generate subpicosecond X-ray pulses, including laser-excited plasma radiation [1], bunch-sliced synchrotron radiation [2], and right-angle Thomson scattering [2], to generate true femtosecond X-ray pulses (<100 fs) with appreciable brightness remains a challenge. The main obstacle is the physical size of the radiator, which dominates the pulse duration broadening. Even the future X-ray free-electron lasers [3] suffer from the same limitation, and the pulse duration is limited to about 200 fs.

In this paper, we propose to use small-angle Thomson scattering (SATS) to generate bright keV radiation with a pulse duration well below 100 fs. In this scheme, the useful longitudinal size of the radiation volume is limited to that comparable to the laser pulse duration, hence the pulse length of the X-ray is largely freed from the physical size of the electron bunch and can be as short as the laser pulse. Meanwhile, for routinely achievable electron quality from modern photocathode guns and the chirped-pulse-amplification ultrafast laser systems, peak spectral brightness comparable to those of the third-generation synchrotron light sources can be achieved. In comparison with other proposals of generating short X-ray pulses in these proceedings, the distinct advantage is its capability of generating X-ray pulses as short as a few fs with no compromise on the peak spectral brightness, hence is well suited for ultrafast dynamic studies.

II. SMALL-ANGLE THOMSON SCATTERING
For Thomson scattering, with the scattering angle $\theta \ll 1$ and the relativistic factor of the electron bunch $\gamma \gg 1$, the energy of the scattered photon is

$$E = E_L \frac{2\gamma^2}{1 + \gamma^2 \theta^2} (1 - \cos \phi), \quad (1)$$

and the differential scattering cross section (after integration over the azimuthal angle) is

$$\frac{d\Sigma}{d\theta} = 8\pi e^2 \gamma^2 \frac{1 + \gamma^4 \theta^4}{(1 + \gamma^2 \theta^2)^4} \theta. \quad (2)$$

Here $E_L$ is the energy of the incident photon, $\phi$ and $\theta$ are, respectively, the angles of the incident and scattered photons with respect to the electron propagation direction, and $r_e$ is the classical electron radius. When $\phi \ll 1$ at $\theta = 0$, we have $\phi = (E/E_L)^{1/2}/\gamma$.

2.1 Pulse duration

Note that, from Eq. (1), one can obtain the same energy for the scattered photons by different combinations of the electron bunch energy and the incidence angle of the incoming photons. An interesting scenario is created when one increases the electron beam energy while reducing the laser incidence angle. In this case the slippage between the incoming laser pulse and the scattered photons can be significantly reduced, thus limiting the longitudinal size of the emitter. This is very favorable for short-pulse X-ray generation. Furthermore, a smaller divergence is expected for the scattered photons at higher electron energies from Eq. (2), which shows the divergence of the scattered photons is approximately $1/\gamma$ as a result of the Lorentz contraction effect.

Consider a Gaussian electron bunch with $\sigma_{x,y,z}$ RMS bunch sizes propagating along the $z$ axis and interacting with a Gaussian laser pulse propagating in the $x$-$z$ plane. The laser has an RMS pulse duration of $c\tau_L < \sigma_z$, and the beams are matched in the vertical direction so that the
laser beam waist $w_0=2\sigma_y$. The pulse duration of the scattered photon burst is the convolution of three factors: the laser pulse length $\tau_L$, the lag between the scattered and the incident photons $(1-\cos\phi)t_c=\sigma_x\phi/2c$, and the projection of the transverse laser beam size along the $z$ axis, which is $(1-\cos\phi)t'_c=\sigma_y\sin\phi/c \approx \sigma_y/2c$. Here $t_c=\sigma_x/c\sin\phi=\sigma_x/c\phi$ is the time needed for the laser pulse to cross the electron bunch (we assume $\sigma_x \geq \sigma_y$), and $t'_c=\sigma_y\cos\phi/c\sin\phi$. Hence the pulse duration of the scattered photons is,

$$\tau = \tau_L \left[ 1 + \left(1 + \frac{\sigma_x^2 + \sigma_y^2}{4\tau_L^2c^2}\right)\phi^2 \right]^{1/2}. \quad (3)$$

Here $w_0=2\sigma_y$ is used. Equation (3) reveals the most important characteristics of the small-angle Thomson scattering scheme, i.e., its capability to generate an X-ray burst with pulse duration comparable to that of the incident laser, which occurs with reasonably focused electron bunches for small enough laser incidence angle. Under this condition, the laser and electron beam sizes play no role in determining the pulse duration, and the short pulse length of the scattered radiation is the result of a ‘sliced’ Thomson scattering in which only those electrons underlying the laser pulse are scattering the laser photons, and the scattered photons are physically ‘locked’ with respect to the laser pulse.

The result is depicted in Fig. 1 (a), where the numerically calculated X-ray pulse duration generated by scattering a FWHM 20-fs (RMS duration of 8.5 fs) laser pulse off a 0.2-ps electron bunch is plotted as a function of the electron bunch transverse sizes and energies. The calculation is performed by numerically integrating the distribution function (assumed to be Gaussian) of the electron bunch and the laser pulse coupled by Eqs. (1, 2). The laser wavelength is at 800 nm (1.55 eV), and the peak of the angle-integrated X-ray spectra is kept at 8 keV by adjusting the laser incidence angle over the range from 380 to 19 mrad. Clearly, X-ray pulse duration down to
20 to 30 fs can be achieved, a regime so far only available at visible to VUV wavelengths. In the calculation, a conservative normalized electron beam emittance of $10^{-5}$ m rad is used, which is a factor of 2-3 larger than that produced from modern photocathode guns.

Although in the numerical examples throughout this paper we use an FWHM laser pulse duration of 20 fs, the SATS scheme can work with lasers having much shorter pulse duration to generate even shorter X-ray pulses. The condition for relaying the laser pulse duration to the X-ray radiation within a relative broadening factor of $\eta = \sigma \tau_\text{r}$ can be derived from Eq. (3), which determines the maximum electron bunch transverse size (for a round electron bunch)

$$\sigma_{x,y,\text{max}} \approx 2 \left( \frac{\eta}{\gamma} \right)^{1/2} \gamma c \tau_L. \quad (3a)$$

Here $\phi = (E/E_L)^{1/2}/\gamma$ is used. As an example, for a $\gamma=1300$, $E=8$ keV and $E_L=1.55$ eV (800 nm radiation), to maintain the pulse duration of the laser within an error of $\eta=20\%$, the beam size needed is approximately 16 times the laser pulse length. Even for a 5-fs FWHM pulse duration, this gives a 24-µm FWHM transverse bunch size, a moderate number for high quality, well focused electron beams. The same longitudinal or transverse beam size would generate 80-fs pulses in regular Thomson scattering and synchrotron radiation schemes.

### 2.2 Photon production and spectra

However, there are two disadvantages associated with small laser incidence angles. The apparent one is that the number of the scattered photons can be significantly reduced. This is due to the fact that the effective laser flux seen by the electrons becomes smaller. In the laboratory frame, the electrons (propagating at $\sim c$) see the photons propagating at a speed of $c(1-\cos \phi) = c \phi^2 / 2$ along the $z$ axis, which is the only useful component of the photon flux (the
transverse scattering cross section is collapsed by Lorentz contraction effect). Considering that
the interacting electrons are those underlying the laser pulse and the interaction time is \( t_c \), using
simple geometrical considerations, the total number of scattered photons is calculated as

\[
n = \frac{\Sigma_0 \, N_e \, N_p \, \sigma_0}{4\pi \, \sigma_y \, \sigma_z}.
\]

Here \( N_{e,p} \) are numbers of electrons and photons, \( \Sigma_0 \) is the integrated scattering cross section over
the acceptance angle (when integrated over all angles, it is the Thomson scattering cross section).

The second disadvantage is that the full bandwidth becomes larger as the incidence angle
becomes smaller. To understand this, we first calculate the bandwidth at a particular scattering
angle, which can be obtained by differentiating Eq. (1) using Gaussian energy and angular
distributions for the laser electron bunches,

\[
\frac{\Delta E}{E} \approx \left( \frac{\sigma_{\phi}^2 + \sigma_{\chi'}^2 + \sigma_{\gamma'}^2}{\phi^2} + 4\sigma_e^2 + \sigma_L^2 \right)^{1/2}.
\]

Here \( \sigma_{\chi',\gamma'} \) are the electron beam divergence, \( \sigma_e \) is the electron bunch energy spread, \( \sigma_0 = \lambda_t/4\pi\sigma_y \)
and \( \sigma_L = \lambda_t/4\pi \tau_L \) are the diffraction-limited divergence and the transform-limited bandwidth of
the laser pulse. To obtain the angle-integrated bandwidth, one needs to numerically convolve Eq.
(5) with Eqs. (1, 2), and, at incident angles comparable to or smaller than the laser divergence,
spectrum broadening due to laser divergence dominates,

\[
\left( \frac{\Delta E}{E} \right)_{\text{int}} = 2 \frac{\sigma_{\phi}}{\phi} = \frac{\lambda_t}{2\pi\sigma_0 \phi}.
\]

The spectrum broadening is illustrated in Fig. 1 (b), where the numerically calculated
FWHM bandwidth of the angle-integrated spectra as a function of the beam energy and
transverse beam size is given. The bandwidth changes from below 30% for low beam energies
and large transverse sizes, to ~ 200% at high beam energies with small transverse beam sizes, in agreement with Eq. (5a).

Summarizing Eqs. (3-5), the average photon flux can be estimated as

\[
F \approx \frac{\sum_0}{4\pi} \frac{N_e N_p}{\sigma_z} \frac{\delta_{BW}}{\lambda} \frac{1}{\gamma^2} f, \tag{6}
\]

here \( \delta_{BW} \) is the required bandwidth for the experiment, \( \lambda \) is the wavelength of the scattered photons, and \( f \) is the repetition rate. We used \( \phi = (E/E_L)^{1/2}/\gamma = (\lambda_4/\lambda)^{1/2}/\gamma \) for obtaining Eq. (6).

From Eq. (6), it is clear that the photon flux decreases rapidly as the electron bunch becomes more energetic. The numerically calculated photon flux is given in Fig. 2 (a) for the same condition as in Fig. 1 except that a 2-J per pulse laser energy at 6 Hz is used. Note that the bandwidth of the angle-integrated spectrum is used.

Obviously, for more efficient scattering or higher photon flux, larger laser incidence angles are more desirable. From Eq. (3a), for a fixed bunch size with a relative broadening factor of \( \eta = \sigma/L - 1 \), the minimum electron bunch energy (corresponding to the maximum laser incidence angle) that maximizes the photon flux is,

\[
\gamma_{min} \approx \frac{\sigma_{L,\gamma}}{2c \tau_L} \left( \frac{E}{\eta E_L} \right)^{1/2}. \tag{7}
\]

As an example, for a laser FWHM pulse length of 20 fs and electron bunch size of 11 mm RMS, \( \gamma_{min} = 348 \), or 180 MeV of beam energy. This would increase the photon flux by more than a factor of 10 when compared with the case when \( \gamma = 1270 \) (650-MeV beam energy).

2.3 Divergence and peak spectral brightness
Interestingly, for low-emittance electron bunches, even with fewer scattered photons and broader spectra, we find that the spectral brightness (defined as photon flux per unit solid angle and area) of the X-ray burst does not necessarily degrade at small laser incidence angles, making the SATS source also very useful for experiments that need a high spectral brightness. This is due to the fact that higher beam energy enhances the Lorentz contraction effect and further collapses the divergence of the scattered photons. To understand this, we can write the divergence of the scattered photons as \( \phi_{x,y} \sim (1/\gamma^2 + \sigma_{x,y}^2)^{1/2} \), which is a convolution of the Lorentz contraction effect determined by Eq. (2) as \( 1/\gamma \) and the divergence of the electron bunches \( \sigma_{x,y} \). For high-quality, low-emittance electron bunches, the bunch divergence can be much smaller in most of the cases considered in this paper, hence the divergence of the scattered photons can be approximated by \( \propto 1/\gamma^2 \), which decreases rapidly as electron beam energy increases. It should also be noted that, in a linac, the bunch divergence also decreases as the beam energy increases due to the scaling of the geometrical emittance with the beam energy \( \varepsilon = \varepsilon_0/\gamma \).

This reduction of the divergence roughly compensates the reduced photon production and the broadened spectrum at smaller laser incidence angle. In addition, in a linac, the above-mentioned geometrical emittance will make the bunch much easier to focus for higher scattering efficiency and spectral brightness. To summarize, the achievable peak spectral brightness of the scattered photons can be estimated as

\[
B \approx \frac{\sqrt{2} \Sigma_0 N_p N_e}{16\pi^3} \frac{\delta_{BW}}{\sigma_x \sigma_y \sigma_z \tau_L} \frac{\delta_{BW}}{\lambda},
\]

Equation (8) is valid when \( 1/\gamma > \sigma_{x,y} \). It should also be mentioned that, due to the scattering geometry, the source sizes in the \( x \) and \( y \) axes are calculated differently. In the \( y \) direction, it is determined by overlapping two Gaussian profiles with the same width; hence the
profile is narrowed and is $\sigma_y/\sqrt{2}$. In the $x$ dimension, the laser pulse ‘scans’ the electron bunch; hence the bunch size determines the source size, which is $\sim \sigma_x$.

The numerically calculated peak spectral brightness is given in Fig. 2 (b). One sees that there is clearly an optimal beam energy that maximizes the spectral brightness, which occurs when $1/\gamma < \sigma_{x',y'}$ and the laser divergence $2\sigma_y/\phi$ starts to dominate the angle-integrated bandwidth $(\Delta E/E)_{int}$.

III. DISCUSSION

3.1 High peak brightness

Figure 2 also clearly illustrates the importance of the phase-space density of the electron bunch for high brightness as shown in Eqs. (6, 8). Generally, the denser the bunch in the phase space, the higher the brightness, thus highlighting the importance of using a linear accelerator for this application.

In comparison with a circular accelerator, such as a synchrotron, a linear accelerator has two major advantages. The first is that it is a one-pass machine, making it possible to preserve the low emittance of electron bunches generated using modern photocathode guns. The second is the freedom of using bunch compressors to shorten the bunch length to well below 1 ps. At the Advanced Photon Source (APS) injector linac [4, 5], for example, normalized RMS emittance smaller than $10^{-5}$ m rad and RMS bunch length of ~0.2 ps have been routinely achieved. With an energy spread of 0.1%, particle-tracking simulation shows it is possible to achieve an 11-µm transverse beam size at 650 MeV with modest effort.

The results in Fig. 2 actually show the projected performance achievable using the APS linac with electron bunch charge of 1 nC. (Note that, to achieve the above-mentioned emittance
and bunch length may be a challenge.) With a laser energy of 2 J and a pulse duration of 20 fs [6], the peak brightness obtainable is about $10^{20}$ photons s$^{-1}$ mm$^{-2}$ mrad$^{-2}$ per 0.1% BW at 8 keV with the beam parameters described above at 650 MeV beam energy ($\gamma \sim 1300$). This is a flux of $\sim 10^5$ photons per second per 0.1% bandwidth in a duration of 20 fs and a cone of 3 mrad. The peak brightness is close to those of the third-generation synchrotron light sources.

3.2 Tunability

By adjusting the laser incidence angle, the peak of the X-ray spectra can be adjusted up to 40 keV with no significant changes in the properties of the scattered photons, as shown in Fig. 3. In Fig. 3 (a), the spectra with peak photon energy from 8 to 40 keV are given, and Fig. 3 (b) gives the pulse duration and peak spectral brightness as a function of the spectrum peak position. Clearly, the duration is almost constant at 20 fs, although the spectrum peak shifts from 8 to 40 keV. The only observed change is the increase in the peak spectral brightness when the spectrum shifts to higher peak photon energy due to the larger laser incidence angle.

3.3 Ponderomotive scattering

With the laser intensity used in this paper, it is necessary to consider the possible ponderomotive scattering of the electrons from the laser field, which might deflect the electrons from the laser focus before they can scatter the photons. The ponderomotive force [7] of the laser field, using the laser strength parameter, can be written as,

$$\frac{d\vec{p}}{dt} = -\frac{mc^2}{\gamma} \vec{\nabla} a^2,$$  

(9)
where $a = 10^{-9} I^{1/2} \lambda_{L}$ is the laser strength parameter with $I$ the laser intensity in W/cm$^2$ and $\lambda_{L}$ in µm; $\vec{p}$ is the electron momentum. In our case, with the laser focus size of $\sigma_x$, we have $\nabla \perp a^2 = a^2 / \sigma_x$ and an interaction time of $t_c = \sigma_x / c \phi$, the maximum change in the transverse momentum can thus be approximated as $\delta p_\perp \approx mca^2 / c \phi$, therefore the relative change of the transverse momentum is $\delta p_\perp / p_\perp \approx (a / c \phi)^2$. In the examples in this paper, with the tightest focus of 11 µm, the focused laser intensity is of the order of $6.6 \times 10^{19}$, and the laser strength parameter is $a = 5.6$. For 650-MeV electron bunches and 8-keV X-ray photons, the laser incidence angle is $\phi = 60$ mrad, and we have $\delta p_\perp / p_\perp \approx 0.5\%$, which is negligibly small. The same argument is applicable to the change in the longitudinal momentum, and we obtain $\delta p_\parallel / p_\parallel \approx (a / c \phi)^2 (\sigma_x / c \tau_\perp \phi)$, which again is very small for the range of $\gamma$ we are interested in. Clearly, the ponderomotive scattering effect is negligible in the regime of interest.

IV. CONCLUSION AND ACKNOWLEDGEMENT

Our calculation is summarized in Table I, which also lists the performance of other sub-picosecond keV X-ray sources, namely the right-angle Thomson scattering and the bunch-sliced synchrotron radiation [2], and that of laser plasma sources [1]. SATS stands out because of two distinctive characteristics: short pulse duration of well below 100 fs and higher peak spectral brightness beyond $10^{20}$ photons s$^{-2}$ mm$^{-2}$ mrad$^{-2}$ per 0.1% bandwidth. Together with the intrinsic synchronization to the laser pulse, it has the potential to become a very useful tool to push the frontier of ultrafast dynamics studies into the sub-100-fs atomic scale in pump probe experiments.

In summary, we propose to use small-angle Thomson scattering for sub-100-fs keV X-ray pulse generation. As an example, we show that, by using the high-quality electron bunches in
the APS injection linac, 8- to 40-keV x-ray sources can be generated with a peak spectral brightness of $10^{20}$ photons s$^{-1}$ mm$^{-2}$ mrad$^{-2}$ per 0.1% bandwidth and with pulse durations of ~20 fs. The technique can also be used for sub-10 fs X-ray pulse generation. The scheme can be optimized either for higher photon flux or for higher spectral brightness by changing the laser incidence angle and the electron bunch energy to fit the experiment’s requirement.

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References

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Figure captions

Figure 1 Contour plots of (a) X-ray pulse FWHM duration in femtoseconds, and (b) angle-integrated X-ray FWHM bandwidth $(\Delta E/E)_{\text{int}}$ as a function of transverse bunch size and energy with an RMS bunch length of 0.212 ps and a normalized emittance of $10^{-5}$ m rad. The laser is a 20-fs Ti: sapphire system at 800 nm. The X-ray spectra peak at 8 keV.

Figure 2 Contour plots of (a) the average photon flux (photons s$^{-1}$ per 0.1% bandwidth), and (b) the spectral brightness (photons s$^{-1}$ mm$^{-2}$ mrad$^{-2}$ per 0.1% bandwidth) as a function of transverse bunch size and beam energy. The RMS bunch length is 0.212 ps, and the normalized emittance is $10^{-5}$ m rad. The laser is a 20-fs, 2-J Ti: sapphire system at 800 nm at 6 Hz. The X-ray spectra peak at 8 keV. A repetition rate of 6 Hz is used when calculating the average photon flux.

Figure 3 (a) Spectra with peak positions at 8 to 40 keV, and (b) peak brightness (dotted line) and pulse duration (solid line) as a function of the spectrum peak position. The bunch energy is 650 MeV with RMS bunch length of 0.212 ps, and the normalized emittance is $10^{-5}$ m rad. The laser is a 20-fs, 2-J, Ti: sapphire system at 800 nm. Shifting the spectrum peak is accomplished by changing the laser incidence angle.
Table I. Summary of the proposed APS SATS X-ray source

<table>
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<tr>
<th></th>
<th>APS Linac&lt;sup&gt;a&lt;/sup&gt;</th>
<th>ALS 90 TS&lt;sup&gt;b&lt;/sup&gt;</th>
<th>ALS Slicing&lt;sup&gt;c&lt;/sup&gt;</th>
<th>Laser Plasma&lt;sup&gt;d&lt;/sup&gt;</th>
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<td>1-10</td>
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<td>~300</td>
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<td>~10&lt;sup&gt;19&lt;/sup&gt;</td>
<td>~10&lt;sup&gt;18&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

a. Operating with a 6-Hz, 20-fs, 2-J, 800-nm laser at 650 MeV beam energy
b. Ref. 2, perspective value
c. Ref. 2, perspective value
d. Ref. 1, experimental data
e. In photons s<sup>-1</sup> per 0.1% bandwidth
f. In photons s<sup>-1</sup> mm<sup>-2</sup> mrad<sup>-2</sup> per 0.1% BW
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