USPAS Course on
4th Generation Light Sources II
ERLs and Thomson Scattering

G. A. Krafft and I. V. Bazarov
Jefferson Lab and Cornell University

Thomson Scattering Sources
1. Thomson Scattering vs. Undulator Radiation
2. Thomson Scattering Sources (TSS):
   1. JLAB
   2. BNL
   3. Duke
   4. Berkeley
   5. Idaho Accelerator Center
   6. Naval Research Lab
3. Other proposals:
   1. Small-Angle Geometry
   2. Laser Electron Storage Ring

Sir J.J. Thomson
Thomson Scattering vs. Undulator Radiation

- Undulator radiation can be looked as Thomson scattering (and vice versa)
- Same signature: polarization, harmonic content when $a_0, K \geq 1$

$$a_0 = \frac{eA_0}{m_e c^2}$$

$$K = \frac{eB_0}{k_p m_e c}$$
Thomson Scattering Same as Short Undulator Radiation

For $K \leq 1$:

$$N_{ph,tot} \approx \alpha K^2 N_p N_e$$

$$\frac{r_e}{\lambda_e} = \frac{1}{137}$$

$$\lambda \approx \frac{\lambda_p}{2\gamma^2} (1 + \gamma^2 \theta^2)$$

useful fraction

$$\sim (\Delta \omega/\omega) \times (\epsilon_\perp/\epsilon_{ph})^2$$

Scaling with undulator period of the formulas above:

- to keep radiation wavelength the same: $\lambda_p \sim \gamma^2$
- to keep the number of photons the same
  - if undulator length is kept the same: $B_0 \sim 1/\gamma$
  - if number of periods is kept the same: $B_0 \sim 1/\gamma^2$

$B_0$ in undulator is limited to $\sim$ Tesla, thus, electron energy is constrained to some multi-GeV, and undulator period to $\sim$ cm for hard x-ray production.
Different Thomson Scattering Geometries

\[ \lambda \approx \frac{\lambda_L}{2\gamma^2} \left(1 + \gamma^2 \theta^2\right) \frac{1}{1 - \cos \phi} \]

- possible advantages include compact design (small \( \gamma \)), fs x-ray pulses
- we’ll look at different examples of TSS: \( \phi = \pi/2 \), \( \phi = \pi \) and \( \phi << 1 \)
Colloquium: Femtosecond x-ray crystallography

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B. Ultrafast protein crystallography

The potentially most rewarding, but also most demanding application of femtosecond x-ray diffraction is the characterization of ultrafast structural processes in biological molecules. From a time-resolved measurement of single-crystal diffraction intensities, the transient changes in electron density of the constituent molecules can be calculated, giving a superbly clear picture of the ultrafast biological reactions. However, in order to determine the electronic density in such large molecules, the intensity of $10^4$ or more different diffraction spots must determined. With only one diffracted photon detected per $10^3$ incident on the sample, and a reasonable minimum of $10^2 - 10^3$ photons in each spot, it is necessary to put at least $10^{11} - 10^{12}$ photons on the sample in order to perform an experiment.

Synchrotron sources can in a single pulse of about 150 ps duration deliver a sufficient number of photons to make single-shot experiments possible. For the much weaker femtosecond x-ray sources the situation is quite different, and it will be necessary to accumulate over many shots, so only multishot samples can be used. Repetition rates of 10 or 20 Hz are common for intense femtosecond lasers, while the system at the ESRF has a maximum frequency of 900 Hz. In experiments, the upper limit to the useful rate will be set by the maximum permitted value of the heat load from the optical excitation pulses. The energy necessary to dissociate all CO molecules once in a crystal of MbCO heats the crystal by about 2 °C (assuming the heat capacity of water), so efficient cooling will be necessary in order to attain high accumulation rates, even if only a minor fraction of the molecules in the sample are dissociated.
Reality Check Against Photon “Starvation”

From undulator:

\[ N_{ph,tot} \approx \alpha K^2 N_p N_e \]

Thomson scattered x-rays:

\[ N_{ph,tot} \sim \frac{\sigma_T}{\text{focused spot area}} N_{ph,L} N_e \]

Laser pulse needed:

\[ N_{ph,L} \sim \frac{\alpha K^2 N_p}{\sigma_T} \sim \frac{\pi (100 \mu m)^2}{665 \text{ mbarn}} \approx 10^{20} \]

or:

\[ \text{or } \sim 10 \text{ J } / \text{ pulse (TW laser)} \]

\[ a_0 = \frac{e A_0}{m_e c^2} \approx 0.85 \times 10^{-9} \lambda_L (\mu m) \sqrt{I_L (\text{W/cm}^2)} \]

\[ a_0 \sim 1 \text{ for } I_L \approx 2.2 \times 10^{18} \text{ W/cm}^2 \]

• can be tough to match laser and electron beams in space-time, i.e.
  only a fraction of electrons or photons will participate in scattering

• rep rate is limited to \( \sim \) kHz (don’t need more for pump probe exp.)
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   5. Idaho Accelerator Center
   6. Japanese Tohuku Group
3. Other proposals:
   1. Small-Angle Geometry
   2. Laser Electron Storage Ring
Demonstration of $8 \times 10^{18}$ photons/second peaked at 1.8 Å in a relativistic Thomson scattering experiment


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(Received 7 February 2000; published 27 September 2000)

$7.6 \times 10^6$ x-ray photons per 3.5 ps pulse are detected within a 1.8–2.3 Å spectral window during a proof-of-principle laser synchrotron source experiment. A 600 MW CO$_2$ laser interacted in a head-on collision with a 60 MeV, 140 A, 3.5 ps electron beam. Both beams were focused to a $\sigma = 32$ $\mu$m spot. Our next plan is to demonstrate $10^{10}$ x-ray photons per pulse using a CO$_2$ laser of $\sim$1 TW peak power.

geometry the x-ray pulse length is defined not just by the laser but by the transverse time of the electron and laser focus that is about 300 fs at the typical rms beam size $\sigma \approx 50$ $\mu$m. In the 180° configuration, the x-ray pulse duration is defined primarily by the electron bunch length $\tau_x = \tau_b + \tau_L/4\gamma^2$, where $\tau_b$ is the electron bunch length, $\tau_L$ is the laser pulse length, and $\gamma$ is the electron beam Lorentz factor. With the 200 fs electron bunches demonstrated from the rf linac [12] and the recent proposal on chirped bunch compression to 10–20 fs [13], the 180° geometry promises the absolute shortest x-ray pulses.

radius that is important for the 90° configuration. Note that the 180° LSS is capable of producing femtosecond x-ray pulses using picosecond and even nanosecond laser pulses (for nanosecond pulses, channeling is required [14]).

In this paper, we describe results of the first proof-of-principle test of the CO$_2$ LSS on the picosecond time scale. We used the ATF 0.6 GW, 180 ps, linearly polarized CO$_2$ laser and the 3.5 ps, 0.5 nC, 60 MeV, low emittance $\varepsilon_n = 2$ mm mrad electron beam and demonstrated an x-ray yield of $2.8 \times 10^7$ photons/pulse, $8 \times 10^{18}$ photons/sec, peaked at 1.8 Å.
TABLE I. ATF CO$_2$ LSS experimental results and near-future design parameters.

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO$_2$ laser</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse length (ps)</td>
<td>180</td>
<td>30</td>
</tr>
<tr>
<td>Pulse energy (J)</td>
<td>0.2</td>
<td>30</td>
</tr>
<tr>
<td>Peak power (GW)</td>
<td>0.6</td>
<td>1000</td>
</tr>
<tr>
<td>rms radius at focus ($\mu$m)</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Waist length (mm)</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Electron beam</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron energy (MeV)</td>
<td>60</td>
<td>60 (70)</td>
</tr>
<tr>
<td>Bunch duration FWHM (ps)</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Bunch charge (nC)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Normalized emittance (mm mrad)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Momentum spread (%)</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>rms radius at focus ($\mu$m)</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td><strong>X rays</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak wavelength (Å)</td>
<td>1.8</td>
<td>2.6 (1.8)</td>
</tr>
<tr>
<td>Pulse duration (ps)</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Photons per pulse (total spectrum)</td>
<td>$2.9 \times 10^7$</td>
<td>$1.3 \times 10^{10}$</td>
</tr>
<tr>
<td>Photons per sec (total spectrum)</td>
<td>$8 \times 10^{18}$</td>
<td>$4 \times 10^{21}$</td>
</tr>
</tbody>
</table>

The aforementioned angular and spectral distributions of the backscattered radiation enter into the expression for brightness $B$, which is a cumulative characteristic of the radiation source

$$B = \frac{N_x \gamma^2}{4(\pi \sigma_b)^2 \tau_b},$$

equal to $2.8 \times 10^{18}$ photons/sec mm$^2$ mrad$^2$ for the present ATF experiment conditions.

0.1 % bw
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Gamma-Ray Production in a Storage Ring Free-Electron Laser


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(Received 24 February 1997)

A nearly monochromatic beam of 100% linearly polarized γ rays has been produced via Compton backscattering inside a free electron laser optical cavity. The beam of 12.2 MeV γ rays was obtained by backscattering 379.4 nm free-electron laser photons from 500 MeV electrons circulating in a storage ring. A detailed description of the γ-ray beam and the outlook for future improvements are presented.

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PACS numbers: 41.60.Cr
1.1 GeV race-track shaped Duke electron storage ring has demonstrated the ability to store an average current of 155 mA at an injection energy of 230–280 MeV. The demonstrated ramping capabilities of this ring provide for an operational beam energy from 230 MeV up to 1.1 GeV. Low emittances (at 500 MeV $\epsilon_x = 4.5$ nm rad and $\epsilon_y < 0.4$ nm rad and horizontal and vertical $\beta$ functions of 4 m at the collision point) are determined by the lattice of the ring, which has a very large dynamic energy aperture of 5%–6% [12]. At present, the energy acceptance is limited by the rf system and is 17.5 MeV (3.5%) at an electron energy of 500 MeV. This makes it possible to preserve all electrons in the $\gamma$-ray production process for all measurements presented below. This “no-loss mode” produces an electron beam having a lifetime of 2–3 h, determined by intrabeam scattering and finite vacuum.
Measured $\gamma$-rays

$2.0 \times 10^5 \gamma$'s per sec
energy of 12.2 MeV

![Graph showing gamma-ray spectrum]

Note: $\gamma$-ray polarization is $\sim 100\%$

The energy spread induced by lasing. This observation makes it apparent that we should prevent lasing of the target bunch for future improvement of the $\gamma$-ray energy resolution.

FIG. 2. Full $\gamma$-ray spectrum as measured by a HPGe detector. The full-energy and first escape peaks associated with the 12.2 MeV $\gamma$-ray beam are clearly visible. The inset shows a Gaussian fit to the full-energy peak. The fit has a FWHM of 120 keV.
Future Plans

In the near future, we are planning to demonstrate the full scale operation of the OK-4/Duke $\gamma$-ray source in the no-loss mode: generation of 2–55 MeV, 100% linearly polarized $\gamma$ rays having a flux of $10^9$–$10^{11}$ per sec. In addition, we should be capable of operating in the “loss” mode ($\gamma$ rays of 55–160 MeV) producing 100% linearly polarized $\gamma$ rays with a flux of $1$–$5 \times 10^8$ per sec. To reach this goal, it will be necessary to extend the operational range of the FEL into the deep uv region ($\sim$10 eV, i.e., 120 nm) at the nominal beam energy of 1 GeV.
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Generation of femtosecond X-rays by 90° Thomson scattering

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We propose Thomson scattering of short pulse laser beams by low energy electron beams at a right angle for generation of femtosecond X-rays. The basic idea is the observation that a low emittance electron beam can be focussed much more tightly in a transverse dimension than in the longitudinal dimension. Therefore much shorter pulses of X-rays can be generated (in the direction of the electron beam) by arranging the laser beam to meet the electron beam at a right angle rather than head on as in the Thomson backscattering configuration. Simple analysis of the process is presented by noting the similarity between the Thomson scattered radiation and the well-understood undulator radiation. Using the parameters of the recently developed femtosecond visible lasers and the high brightness electron guns, it is shown that 1 Å X-ray pulses, of 300 fs duration, containing several $10^5$ photons within 10% bandwidth per collision, can be generated.
1. Introduction

Short radiation pulses are important probes for studying dynamic processes in physics, chemistry and biology. The limiting time scale in many body systems is of the order of $\frac{\hbar}{kT}$, which is about 100 fs at ambient temperature. Thus, there is tremendous potential for radiation sources shorter than 100 fs. Replacing $\hbar \approx 4 \text{eV} \cdot \text{fs}$ and $kT \approx 1/40 \text{eV}$ are quite distinct in the short pulse capability. In Thomson backscattering, the pulse length of the generated X-ray beam is given roughly by the average of electron and the laser pulse lengths. Since it is difficult at present time to generate an intense electron bunch that is much shorter than a few picoseconds, this process does not appear to be useful for generation of femtosecond X-rays. However, we observe that a low emittance electron beam can be focussed tightly to a transverse dimension much smaller than the electron pulse length. Therefore, the possibility arises that much shorter pulses of X-rays can be generated by arranging the laser beam to meet the electron beam at a right angle rather than head-on. This is the basic idea behind the 90° Thomson scattering discussed in this paper. The scheme is illustrated schematically in Fig. 1.

Fig. 1. A schematic illustration of 90° Thomson scattering.
\[ E_0 = \sqrt{2Z_0(dP/dA)}. \]  

(1)

where \( Z_0 = 377 \ \Omega \) is the free space impedance. The laser beam is equivalent to a static magnetic undulator with the peak magnetic field \( B_0 = E_0(1 + \beta \cos \phi)/c \) and period length \( \lambda_u = \lambda_L/(\cos \phi + 1/\beta) \). Here, \( c \) is the speed of light, \( \beta = v/c \), and \( v \) is the speed of the electron, and \( \lambda_L \) is the wavelength of the laser radiation. In the following, we assume that the electrons are relativistic, i.e., \( \gamma = 1/(1 - \beta^2)^{1/2} \gg 1 \), \( \beta = 1 \). For the right angle case, \( \cos \phi = 0 \), we have therefore

\[ B_0 = \frac{E_0}{c}, \]  

(2)

\[ \lambda_u = \lambda_L. \]  

(3)

For an undulator, it is convenient to introduce the deflection parameter \( K \) as follows:

\[ K = eB_0 \lambda_u/2\pi mc. \]  

(4)

\[ \frac{1}{\sigma_r^2} = c^2 \left( \frac{1}{\sigma_L^2} + \frac{1}{\sigma_w^2} \right), \]

where \( \sigma_L \) and \( \sigma_w \) are the rms length and the width of the laser beam, respectively, and \( I_0 \) is the peak laser

\[ \theta = \frac{1}{\gamma} \sqrt{\frac{\lambda - \lambda_1}{\lambda_1}}. \]  

(8)

The number of \( \sigma \)-polarized (polarization parallel to electron trajectory) photons emitted into a given bandwidth \( \Delta \lambda /\lambda = (\lambda - \lambda_1)/\lambda_1 \ll 1 \) is

\[ \Delta n_1 = \pi \sigma K^2 N(\Delta \lambda /\lambda). \]  

(9)

\[ \frac{d\Delta n}{dt} = \pi \alpha K^2 N_{\text{eff}} \left( \frac{\Delta \lambda}{\lambda} \right) \left( \frac{I}{e} \right) \]

\[ \times \frac{\sigma_w (\sigma_L^2 + \sigma_w^2)}{\sqrt{(\sigma_x^2 + \sigma_w^2)(\sigma_x^2 + \sigma_w^2 + \sigma_L^2)}} \]

\[ \times \exp \left( -\frac{t^2}{2\sigma_T^2} \right), \]  

(18)

where \( I \) is the peak electron current, \( e \) is electron charge, and

\[ \sigma_T = \frac{\sigma_x \sqrt{\sigma_x^2 + \sigma_w^2 + \sigma_L^2}}{c \sqrt{\sigma_x^2 + \sigma_w^2 + \sigma_L^2}}. \]  

(19)
lasers [6]. The parameters of the equivalent undulator are: \( \lambda_u = 0.8 \ \mu m, \ B_0 = 500 \ T, \ K = 3.7 \times 10^{-2} \) and \( N_{\text{eff}} = 156 \). The wavelength of the X-rays generated is peaked at \( \lambda_1 = 1 \ \AA \), the rms pulse length calculated from Eq. (19) is \( \sigma_T = 300 \) fs. The number of the X-ray photons within a 10\% bandwidth is, from Eq. (20), \( \Delta n \approx 2.7 \times 10^5 \). The half-angle of the pinhole required to collect 10\% bandwidth is 5.0 mrad. The result is summarized in Table 3.

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<table>
<thead>
<tr>
<th>Table 1</th>
<th>Electron beam</th>
</tr>
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<tbody>
<tr>
<td>Energy</td>
<td>32 MeV ($\gamma = 63$)</td>
</tr>
<tr>
<td>RMS pulse length ($\sigma_z$)</td>
<td>3 ps</td>
</tr>
<tr>
<td>Charge/pulse</td>
<td>1.6 nC</td>
</tr>
<tr>
<td>Normalized rms emittance</td>
<td>5 mm mrad</td>
</tr>
<tr>
<td>Focussed transverse rms width ($\sigma_x$)</td>
<td>50 ( \mu m )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Laser beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength ($\lambda_L$)</td>
<td>8000 ( \AA )</td>
</tr>
<tr>
<td>Energy/pulse</td>
<td>0.2 J</td>
</tr>
<tr>
<td>RMS pulse length ($\sigma_L/c$)</td>
<td>170 fs</td>
</tr>
<tr>
<td>Focussed transverse rms width ($\sigma_w$)</td>
<td>50 ( \mu m )</td>
</tr>
<tr>
<td>Power density (dP/dA)</td>
<td>( 3 \times 10^{19} ) W/m(^2)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Generated X-ray beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength ($\lambda_1$)</td>
<td>1 ( \AA )</td>
</tr>
<tr>
<td>RMS pulse length ($\sigma_T$)</td>
<td>300 fs</td>
</tr>
<tr>
<td>Number of photons ($\Delta \lambda / \lambda = 0.1$)</td>
<td>( 2.7 \times 10^5 )</td>
</tr>
<tr>
<td>Collection angle (2( \theta ))</td>
<td>2\times 5 mrad</td>
</tr>
</tbody>
</table>
Experimental Results

R.W. Shoenlein et. al, Nature (274) 5285

e− beam
50 MeV, 1.3 nC, 90 µm, 20 ps

laser beam
800 nm, 100 fs, 60 mJ, 30 µm

x-ray beam produced
2 × 10^5 ph mm^-2 mrad^-2 s^-1 in
a 15% bandwidth
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Laser-Compton scattering from a 20 MeV electron beam

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Abstract

Laser-Compton scattering (LCS) experiments were carried out at the Idaho Accelerator Center. A 20 MeV electron beam was brought to a head-on collision with a 100 MW 7 ns Nd:YAG laser. We observed clear narrow LCS X-ray spectral peaks resulting from the interaction of the electron beam with the two Nd:YAG laser photon lines of 1064 and 532 nm. The LCS X-ray energy lines and widths were measured as a function of the electron beam energy and energy spread, respectively. The results recorded showed good agreement with the predicted values.

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\textit{Keywords:} Laser; Compton scattering; X-ray; Linear accelerator

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The Layout

- **Machine**: L-band, 1300 MHz, 3 Accelerating stages
- **Injector**: KM gun, 120 keV injection
- **RF system**: 1-20 MW Thomson CSF klystron
- **Bunching**: 2-1/2 subharmonic cavities, 1-6/7 subharmonic cavities, 1 Pseudofrequency waveguide
- **Accelerating system**: Tapered buncher waveguide, 120 keV-2 MeV, Low energy waveguide, 2-8 MeV, High energy waveguide, 8-28 MeV
- **Beam lines**: 0° port high intensity, no energy analysis, 90° port energy analyzed, momentum defining Slits to a minimum of 0.5% energy spread
- **Short pulse**: 10-50 ps, 10nC/pulse
- **Long pulse**: Macropulse width to 4 μs, 1300 MHz fine structure
- **Energy range**: 0.5 - 28 MeV short pulse, 0.5 - 25 MeV long pulse
- **Energy spread**: Nominal 3%, Minimum 0.5%
- **Repetition rate**: Single pulse, 1 - 360 HZ
- **Maximum output at 20 ns wide pulse**: 200 nC/macropulse
- **Maximum output at 4 μs wide pulse**: 2000 nC/macropulse
- **Spot size**: $\sigma_x = 4.77 \pm 0.3 \text{ mm}$, $\sigma_y = 2.82 \pm 0.25 \text{ mm}$
- **Emittance**: $\varepsilon_x = (14.9 \pm 0.4) \pi \text{ mm-mrad}$, $\varepsilon_y = (10.0 \pm 0.1) \pi \text{ mm-mrad}$
Interaction Region

M = Nd:YAG mirror (1064, 532 nm)
M' = Broadband mirror (200 — 1000 nm)
Focal length = 5 m
M — focal point = 5 m
Detector — focal point = 6.8 m
Detector — Kapton window = 1.7 m
Indirect Laser Pulse Measurements

- $E_c = 20 \text{ MeV}$
- $E = 14.67 \pm 0.047 \text{ keV}$
- $\lambda_{\text{Laser}} = 532 \text{ nm}$
- $25.4 \mu\text{m SS filter}$

\[ \tau_{\text{FWHM}} = 9.11 \pm 0.486 \text{ ns} \]
X-ray Measurements

maximum X-ray yield registered during this experiment, for both X-ray lines, 7.35 and 14.75 keV emitted in a cone of opening angle \(1/\gamma\) is equal to \(3 \times 10^5\) photons/bunch which corresponds to an intensity of \(5.6 \times 10^{13} \text{ s}^{-1}\). This intensity is 3 orders of magnitude higher than the highest yield obtained from planar channeling radiation [29]. The brilliance obtained is therefore equal to \(2 \times 10^{11}\).

Fig. 6. (a) LCS spectrum from the interaction of electron beam and laser fundamental and second harmonic lines. (b) LCS spectrum using a 25.4 \(\mu\text{m}\) SS foil as a high-energy filter.
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Compact Source of Tunable, Monochromatic, Picosecond X rays

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FIGURE 11
ISS interaction configuration.

FIGURE 12
The NRL 4 MeV RF electron gun beam line. The 20 MW S-band klystron is shown on the left and the electron beam propagates toward the reader on the right.

FIGURE 13
Number of x-ray photons generated per pulse as a function of electron beam energy and laser beam energy. The two straight lines indicate the predicted photon numbers for laser beam energies of 3 J and 5 J, respectively.
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   5. Idaho Accelerator Center
   6. Naval Research Lab
3. Other proposals:
   1. Small-Angle Geometry
   2. Laser Electron Storage Ring
Small-angle Thomson scattering of ultrafast laser pulses for bright, sub-100-fs x-ray radiation

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We propose a scheme for bright sub-100-fs 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 and 40 keV can be generated with pulse duration comparable to that of the incoming laser pulse and with peak spectral brightness close to that of the third-generation synchrotron light sources of \(\sim 10^{20}\) photons s\(^{-1}\) mm\(^{-2}\) mrad\(^{-2}\) per 10\(^{-3}\) bandwidth. A preliminary dynamic calculation is performed to understand the property of this novel scattering scheme with relativistic laser intensities.

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

Here \(\omega_0 = 2\sigma_y\) is used. Equation (3) reveals an important characteristic 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. This occurs with reasonably focused electron bunches and 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.
FIG. 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 \(10^{-5}\) mrad. The laser is a 20-fs Ti:sapphire system at 800 nm. The x-ray spectra peak at 8 keV.

FIG. 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 \(10^{-5}\) mrad. 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.
Note: state-of-the-art peak brightness from 3rd generation light sources approaches $10^{24}$ photons s$^{-1}$ mm$^{-2}$ mrad$^{-2}$ per 0.1% bw, and average flux is $10^{15}$ photons s$^{-1}$ per 0.1% bw.
<table>
<thead>
<tr>
<th>Wavelength (Å)</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>BNL 180 TS&lt;sup&gt;d&lt;/sup&gt;</th>
<th>Laser plasma&lt;sup&gt;e&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5–0.3</td>
<td>0.4</td>
<td>6</td>
<td>1.8</td>
<td>1–10</td>
<td>10</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>6</td>
<td>100</td>
<td>10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>3500</td>
<td>10&lt;sup&gt;5&lt;/sup&gt;</td>
</tr>
<tr>
<td>Pulse length (fs)</td>
<td>20</td>
<td>300</td>
<td>~100</td>
<td>10&lt;sup&gt;9&lt;/sup&gt;</td>
<td>4&lt;sup&gt;π&lt;/sup&gt;</td>
</tr>
<tr>
<td>Average photon flux&lt;sup&gt;f&lt;/sup&gt;</td>
<td>10&lt;sup&gt;6&lt;/sup&gt;</td>
<td>10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>10&lt;sup&gt;7&lt;/sup&gt;</td>
<td>10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>10&lt;sup&gt;9&lt;/sup&gt;</td>
</tr>
<tr>
<td>Divergence (mrad)</td>
<td>3</td>
<td>10</td>
<td>0.6</td>
<td>28%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Bandwidth&lt;sup&gt;g&lt;/sup&gt;</td>
<td>67%–200%</td>
<td>80%</td>
<td>~10&lt;sup&gt;10&lt;/sup&gt;</td>
<td>28%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Peak brightness&lt;sup&gt;h&lt;/sup&gt;</td>
<td>~10&lt;sup&gt;20&lt;/sup&gt;</td>
<td>3 × 10&lt;sup&gt;15&lt;/sup&gt;</td>
<td>~10&lt;sup&gt;19&lt;/sup&gt;</td>
<td>10&lt;sup&gt;16&lt;/sup&gt;</td>
<td>~10&lt;sup&gt;18&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup>Operating with a 6-Hz, 20-fs, 2-J, 800-nm laser at 650 MeV beam energy may need a factor of 2–3 adjustment for saturation effect.

<sup>b</sup>Reference [6], perspective value.

<sup>c</sup>Reference [11], perspective value.

<sup>d</sup>Reference [8], experimental data.

<sup>e</sup>Reference [10], experimental data.

<sup>f</sup>In photons s<sup>−1</sup> per 0.1% bandwidth.

<sup>g</sup>In photons s<sup>−1</sup> mm<sup>−2</sup> mrad<sup>−2</sup> per 0.1% BW.

Note: different laser parameters were used for different Thomson scattering sources.

The major challenge for implementing the SATS is to synchronize the electron bunch and the laser pulse accurately to minimize the brightness fluctuation. Analysis shows that the average spectral brightness will be reduced by a factor of [1 + (cτ<sub>j</sub> / σ<sub>x</sub>)<sup>2</sup>]<sup>−1/2</sup> for a jitter of τ<sub>j</sub> between the laser pulse and the electron bunch. With a bunch length of 0.2 ps, and a 1-ps jitter (measured between the current linac and the photocathode gun drive laser at the APS injection linac), a 5-times reduction on the average brightness is expected. Lengthening the bunch length to the jitter size can give a better shot-to-shot fluctuation but lower nominal peak brightness. However, because the same laser pulse used for x-ray production can also be used to pump the sample under study, very accurate timing for a pump-probe experiment can be expected. For other x-ray sources not shown.
Peak brightness alone can be misleading

Single photon peak brightness: \[ B_{\text{peak}} = \frac{1}{(2\pi)^3 \left( \frac{\hbar}{2} \right)^3} \]

or in conventional units:

\[ B_{\text{peak}} \text{ (photon s}^{-1}\text{mm}^{-2}\text{mrad}^{-2} \text{ per 0.1\% bw)} = 2.4 \times 10^{24} / (\lambda (\text{Å}))^3 \]

peak brightness @ 1 Å when photon degeneracy is 1

Summary

Thomson scattering sources can provide \( \sim 10^{3-4} \) shorter pulses than that of 3\textsuperscript{rd} generation light sources, with peak brightness lower by at least \( \sim 10^{3-4} \) and average flux lower by at least \( 10^{9-10} \) assuming state-of-the-art rep rate for laser. Even if the rep rate of Thomson scattering event were somehow improved to some sub-GHz (c.f. next project), average flux would still be \( \sim 10^{3-4} \) when compared to a 3\textsuperscript{rd} generation light sources.
Outline

1. Thomson Scattering vs. Undulator Radiation
2. Thomson Scattering Sources (TSS):
   1. JLAB
   2. BNL
   3. Duke
   4. Berkeley
   5. Idaho Accelerator Center
   6. Naval Research Lab
3. Other proposals:
   1. Small-Angle Geometry
   2. Laser Electron Storage Ring
Laser-Electron Storage Ring

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(Received 30 September 1997; revised manuscript received 9 December 1997)

A compact laser-electron storage ring (LESR) is proposed for electron beam cooling or x-ray generation. The LESR uses an intense laser pulse stored in a high-finesse resonator to interact repetitively with a circulating electron beam in the energy range from a few MeV to a few hundred MeV. The rapid damping caused by laser-electron interaction counterbalances the intrabeam scattering effect, thus allowing electron beams with relatively low energy to be cooled or stabilized in the storage ring to very low transverse emittances. Intense x rays are produced simultaneously from Compton backscattering and can be used for x-ray lithography and other applications. [S0031-9007(97)05245-9]

PACS numbers: 29.20.Dh, 07.85.Fv, 29.27.Eg
General Idea

laser field acts like a static wiggler or undulator with the peak magnetic field given by [3]

$$B_W = \frac{2}{c} \sqrt{2Z_0 I},$$

(1)

where $I$ is the laser intensity, and $Z_0 = (c\varepsilon_0)^{-1} = 377 \ \Omega$ is the free space impedance. The factor of 2 in front of Eq. (1) is due to the addition of the magnetic and electrical forces in the electromagnetic wave. The radiated power becomes [12]

$$P_\gamma = \frac{4\pi \varepsilon_0}{3} r_e c^3 \gamma^2 B_W = \frac{32\pi}{3} r_e^2 \gamma^2 I,$$

(2)

FIG. 1. The schematic diagram of a laser-electron storage ring.

phase space damping rate: $\propto \varepsilon \frac{\langle P_{ph} \rangle}{E}$

$$P_{ph} \propto \frac{E^4}{\rho^2}$$

due to bends alone, i.e. small

phase space excitation rate: $\propto \frac{1}{E^2} \langle \dot{N}_{ph} \langle E_{ph}^2 \rangle \rangle_{ring}$
the ring, the average damping rate to the normalized transverse emittances $\varepsilon_{x,y}^{n}$ is given by

$$\Gamma_{x,y}^{RLC} = -\frac{1}{\varepsilon_{x,y}^{n}} \left\langle \frac{d\varepsilon_{x,y}^{n}}{dt} \right\rangle = \frac{1}{n_{d}T_{\text{rev}}} = \frac{\Delta E_{\gamma}}{E} \frac{1}{T_{\text{rev}}}. \quad (5)$$

at the energy range we consider, the average quantum excitation rate becomes

$$\left\langle \frac{d\varepsilon_{x,y}^{n}}{dt} \right\rangle_{\text{QE}} = \frac{3}{10} \frac{\lambda_{c}}{\lambda_{L}} \frac{(\Delta E)_{\gamma}}{E} \frac{\beta_{x,y}^{*}}{T_{\text{rev}}}. \quad (8)$$
Theoretical emittance & energy spread

The balance between the damping rate Eq. (5) and the excitation rate Eq. (8) leads to the minimum normalized transverse emittances

\[ (\varepsilon_{x,y}^n)_{\text{min}} = \frac{3}{10} \frac{\lambda_c}{\lambda_L} \beta_{x,y}^r. \]  

Note: large initial emittance can hinder the damping

In the longitudinal dimension, the energy spread can be increased by the energy fluctuation of the scattered photons. Averaging over one revolution time, we obtain the rate of quantum excitation to the energy spread

\[ \left< \frac{d(\sigma_E^2)}{dt} \right>_{\text{QE}} = \frac{1}{T_{\text{rev}}} \int_0^{\omega_m} d\omega \left( \hbar \omega \right)^2 \frac{dN_{\gamma}}{d\omega} \]

\[ = \frac{7}{10} \frac{\hbar \omega_{10} \Delta E_{\gamma}}{T_{\text{rev}}}. \]  

However, the energy spread \( \sigma_E^2 \) is also damped as in a normal storage ring [13]:

\[ \frac{1}{\sigma_E^2} \left< \frac{d(\sigma_E^2)}{dt} \right> = -2 \frac{\Delta E_{\gamma}/E}{T_{\text{rev}}} \equiv -\Gamma_s^{\text{RLC}}. \]  

The minimum energy spread is reached when both effects cancel. Thus, we have

\[ (\sigma_{\delta})_{\text{min}} \equiv \left( \frac{\sigma_E}{E} \right)_{\text{min}} = \sqrt{\frac{7}{5}} \frac{\lambda_c}{\lambda_L} \gamma. \]
the Fabry-Perot resonators are made of mirrors with total reflectivity $R = 99.99\%$ [finesse $F \approx \pi/(1 - R) \approx 3.14 \times 10^4$]. To simplify the intrabeam scattering calculations, we consider a round beam for both cases.

**laser peak power:**  0.2 TW (transient)  
**rep rate:**  0.1 GHz (steady)  
**laser power req.d:**  200 W

<table>
<thead>
<tr>
<th>Laser and resonator parameters</th>
<th>Transient</th>
<th>Steady state</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength [(\mu\text{m})]</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Flash energy in the resonator</td>
<td>2 J(^a)</td>
<td>20 mJ(^b)</td>
</tr>
<tr>
<td>Laser pulse length [mm]</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Rayleigh range [mm]</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Focal transverse rms size [(\mu\text{m})]</td>
<td>20</td>
<td>25</td>
</tr>
</tbody>
</table>

**Electron storage ring parameters**

<table>
<thead>
<tr>
<th>Energy [MeV]</th>
<th>100</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of electrons</td>
<td>(1.3 \times 10^{10})</td>
<td>(1.1 \times 10^{10})</td>
</tr>
<tr>
<td>Average ring radius [m]</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Horizontal/vertical tune</td>
<td>(~10)</td>
<td>(~10)</td>
</tr>
<tr>
<td>Energy loss per turn [keV]</td>
<td>25</td>
<td>1</td>
</tr>
<tr>
<td>Trans. damping time [(\mu\text{sec})]</td>
<td>80</td>
<td>80 msec</td>
</tr>
<tr>
<td>Equil. energy spread [%]</td>
<td>2.6(^c)</td>
<td>2.3(^d)</td>
</tr>
<tr>
<td>rf frequency [MHz]</td>
<td>2856</td>
<td>1428</td>
</tr>
<tr>
<td>rf peak voltage [MV]</td>
<td>2</td>
<td>60 KV</td>
</tr>
<tr>
<td>Momentum acceptance [%]</td>
<td>15</td>
<td>23</td>
</tr>
<tr>
<td>rms bunch length [mm]</td>
<td>5.9</td>
<td>6.6</td>
</tr>
<tr>
<td>Beta function at IP [cm]</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Equil. norm. long. emit. [mm]</td>
<td>31</td>
<td>2.4</td>
</tr>
<tr>
<td>Equil. norm. trans. emit. [mm]</td>
<td>(1 \times 10^{-7})</td>
<td>(6 \times 10^{-6})</td>
</tr>
<tr>
<td>Max. space charge tune shift [%]</td>
<td>0.012</td>
<td>0.19</td>
</tr>
</tbody>
</table>

**X-ray parameters**

<table>
<thead>
<tr>
<th>Wavelength [(\text{pm})]</th>
<th>6.25 pm</th>
<th>1 nm</th>
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</thead>
<tbody>
<tr>
<td>Photon energy [keV]</td>
<td>200</td>
<td>1.24</td>
</tr>
<tr>
<td>Photon flux [(\text{sec}^{-1})]</td>
<td>(2.6 \times 10^{20})</td>
<td>(9.1 \times 10^{14})</td>
</tr>
</tbody>
</table>

\(^a\)Maximum flash energy.  
\(^b\)Constant flash energy.  
\(^c\)Determined by quantum excitation effect.  
\(^d\)Determined by both quantum excitation and intrabeam scattering effects.  
\(^e\)Peak x-ray flux.  
\(^f\)Average x-ray flux.