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

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Thomson Scattering Sources

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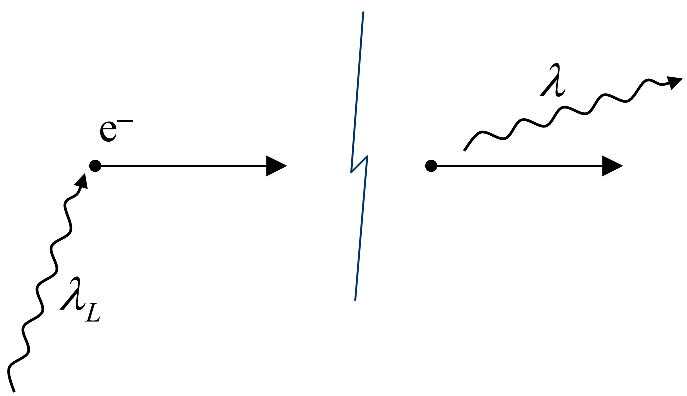
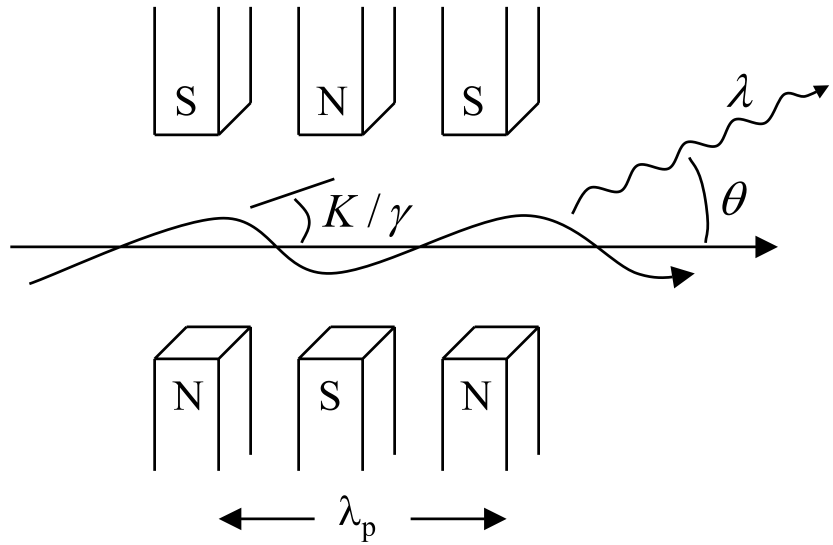
Thomson Scatter Sources & Related Proposals

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





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

$$K = \frac{eB_0}{k_p m_e c}$$

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

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

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

$\lambda / 4\pi$

Scaling with undulator period of the formulas above:

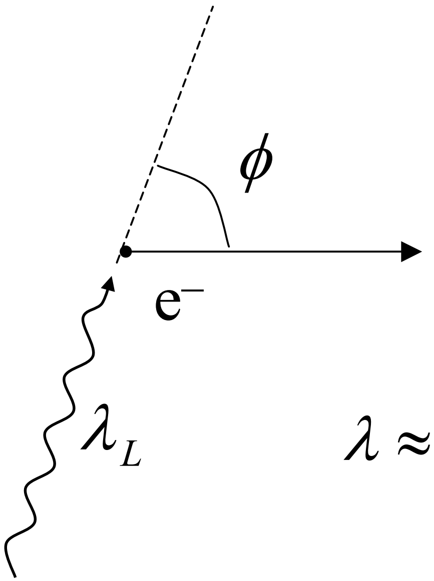
- to keep radiation wavelength the same: $\lambda_p \sim \gamma^2$
- to keep the number of photons the same

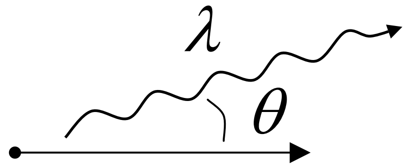
  if undulator length is kept the same: $B_0 \sim 1/\gamma$

  if number of periods is kept the same: $B_0 \sim 1/\gamma^2$

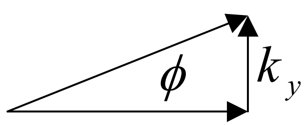
B_0 in undulator is limited to ~ Tesla, thus, electron energy is constrained to some multi-GeV, and undulator period to ~ cm for hard x-ray production.

Different Thomson Scattering Geometries

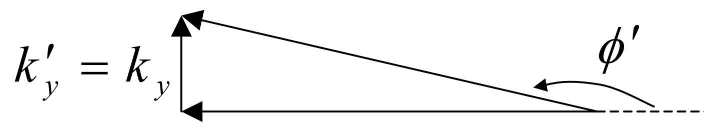




$$\lambda \approx \frac{\lambda_L}{2\gamma^2}(1+\gamma^2\theta^2)\frac{1}{1-\cos\phi}$$



S



S′

$$\frac{d\sigma_T}{d\Omega'} = r_e^2 \sin^2\Theta'$$

$$\sigma_T = \frac{8}{3}\pi r_e^2 = 665 \text{ mbarn}$$

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

Photons Wanted

REVIEWS OF MODERN PHYSICS, VOLUME 73, JANUARY 2001

Colloquium: Femtosecond x-ray crystallography

$\sim h / kT$

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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 10^5 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: $N_{ph,tot} \sim \dfrac{\sigma_T}{\text{focused spot area}} N_{ph,L} N_e$

} mostly incoherent photons

Laser pulse needed:

~ 1

$$N_{ph,L} \sim \alpha K^2 N_p \frac{\text{focused spot area}}{\sigma_T} \sim \frac{\pi \frac{(100\ \mu\text{m})^2}{4}}{665\ \text{mbarn}} \sim 10^{20}$$

or: or ~ 10 J / pulse (TW laser)

$$a_0 = eA_0 / m_e c^2 \approx 0.85 \times 10^{-9} \lambda_L(\mu\text{m}) \sqrt{I_L(\text{W/cm}^2)}$$

$a_0 \sim 1$ 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 ~ kHz (don't need more for pump probe exp.)

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    6. Japanese Tohuku Group
3. Other proposals:
    1. Small-Angle Geometry
    2. Laser Electron Storage Ring

Demonstration of 8×10^{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)

7.6×10^6 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 ~1 TW peak power.

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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 τ_b is the electron bunch length, τ_L is the laser pulse length, and γ 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.

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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 2.8×10^7 photons/pulse, 8×10^{18} photons/sec, peaked at 1.8 Å.

TABLE I. ATF CO_2 LSS experimental results and near-future design parameters.

Parameter	1st stage (1999)	2nd stage (2000)
CO_2 laser		
Pulse length (ps)	180	30
Pulse energy (J)	0.2	30
Peak power (GW)	0.6	1000
rms radius at focus (μm)	32	32
Waist length (mm)	2.5	2.5
Electron beam		
Electron energy (MeV)	60	60 (70)
Bunch duration FWHM (ps)	3.5	3.5
Bunch charge (nC)	0.5	0.5
Normalized emittance (mm mrad)	2	2
Momentum spread (%)	0.15	0.15
rms radius at focus (μm)	32	32
X rays		
Peak wavelength (Å)	1.8	2.6 (1.8)
Pulse duration (ps)	3.5	3.5
Photons per pulse (total spectrum)	2.9×10^7	1.3×10^{10}
Photons per sec (total spectrum)	8×10^{18}	4×10^{21}

peak

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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

peak

$$B = \frac{N_x \gamma^2}{4(\pi\sigma_b)^2\tau_b}, \qquad (10)$$

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

0.1 % bw

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Duke FEL γ-production

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Gamma-Ray Production in a Storage Ring Free-Electron Laser

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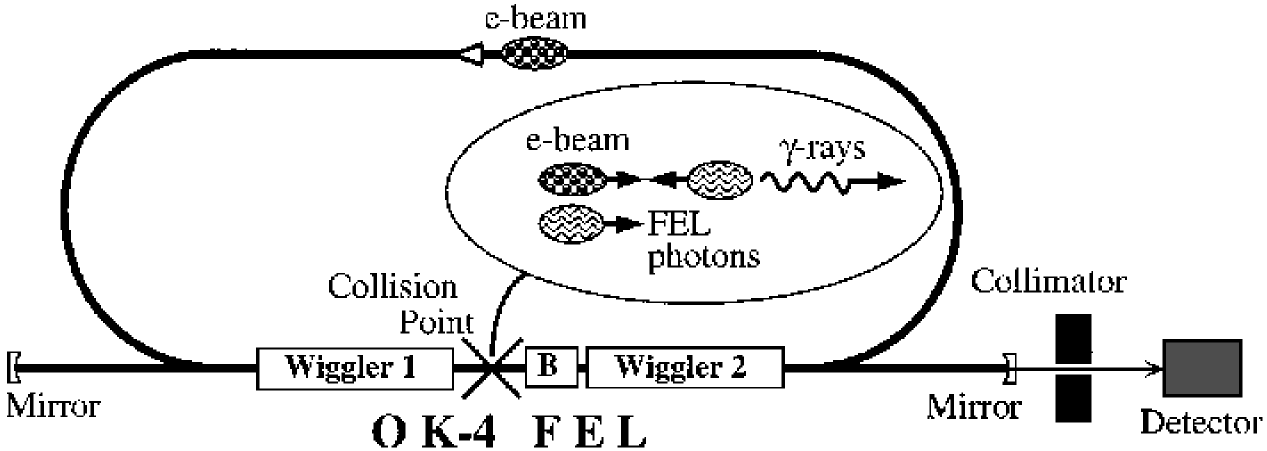
A nearly monochromatic beam of 100% linearly polarized γ rays has been produced via Compton backscattering inside a free electron laser optical cavity. The beam of 12.2 MeV γ rays was obtained by backscattering 379.4 nm free-electron laser photons from 500 MeV electrons circulating in a storage ring. A detailed description of the γ-ray beam and the outlook for future improvements are presented. [S0031-9007(97)03322-X]

PACS numbers: 41.60.Cr

Machine Description



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 β 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 γ-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 γ-rays

2.0×10^5 γ's per sec energy of 12.2 MeV.

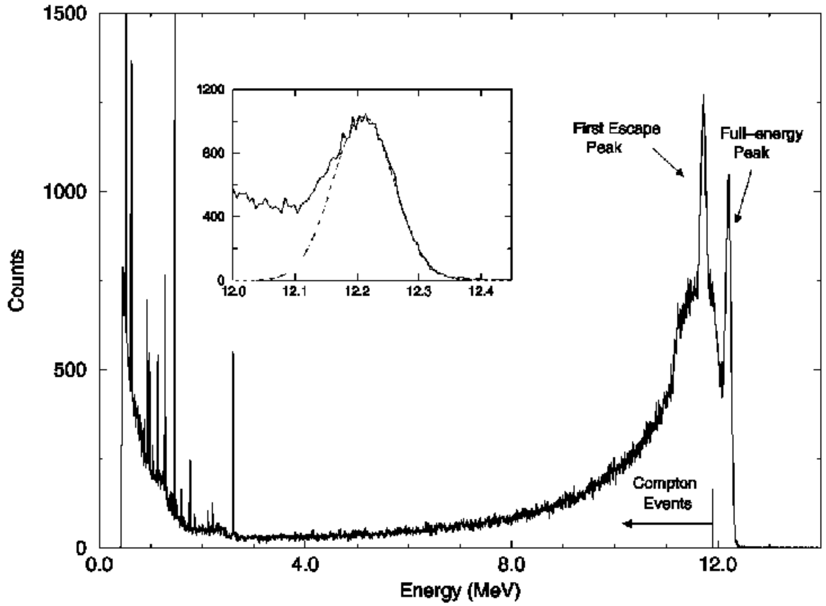


FIG. 2. Full γ-ray spectrum as measured by a HPGe detector. The full-energy and first escape peaks associated with the 12.2 MeV γ-ray beam are clearly visible. The inset shows a Gaussian fit to the full-energy peak. The fit has a FWHM of 120 keV.

an energy spread of 1.25%.

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 γ-ray energy resolution.

Note: γ-ray polarization is ~ 100 %

Future Plans

In the near future, we are planning to demonstrate the full scale operation of the OK-4/Duke γ-ray source in the no-loss mode: generation of 2–55 MeV, 100% linearly polarized γ rays having a flux of $10^9 - 10^{11}$ per sec. In addition, we should be capable of operating in the "loss" mode (γ rays of 55–160 MeV) producing 100% linearly polarized γ 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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Nuclear Instruments and Methods in Physics Research A 341 (1994) 351–354
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

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 h/kT, which is about 100 fs at ambient temperature. Thus, there is tremendous potential for radiation sources shorter than 100 fs. Re- ...

$h \approx 4\ eV{\cdot}fs$

$kT \approx 1/40\ eV$

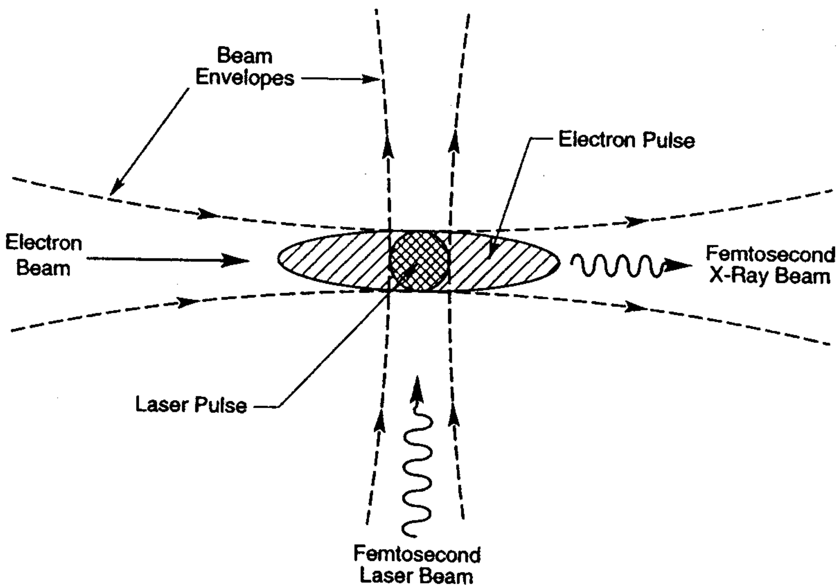

Fig. 1. A schematic illustration of 90° Thomson scattering.

... 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.

?

...

$$E_0 = \sqrt{2Z_0(\mathrm{d}P/\mathrm{d}A)}\,. \qquad (1)$$

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 λ_L is the wavelength of the laser radiation. In the following, we assume that the electrons are relativistic, i.e., $\gamma = 1/(1-\beta^2)^{1/2} \gg 1$, $\beta \approx 1$. For the right angle case, $\cos\phi = 0$, we have therefore

$$B_0 = E_0/c, \qquad (2)$$

$$\lambda_u = \lambda_L. \qquad (3)$$

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

$$K = eB_0\lambda_u/2\pi mc. \qquad (4)$$

...

$$N_{\mathrm{eff}} = 2\sqrt{\pi}\,c\sigma_\tau/\lambda_L. \qquad \frac{1}{\sigma_\tau^2} = c^2\left(\frac{1}{\sigma_L^2} + \frac{1}{\sigma_w^2}\right),$$

where σ_L and σ_w are the rms length and the width of the laser beam, respectively, and I_0 is the peak laser

...

$$\theta = \frac{1}{\gamma}\sqrt{\frac{\lambda - \lambda_1}{\lambda_1}}\,. \qquad (8)$$

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

$$\Delta n_1 = \pi\alpha K^2 N(\Delta\lambda/\lambda). \qquad (9)$$

...

$$\frac{\mathrm{d}\Delta n}{\mathrm{d}t} = \pi\alpha K^2 N_{\mathrm{eff}}\left(\frac{\Delta\lambda}{\lambda}\right)\left(\frac{I}{e}\right) \times \frac{\sigma_w\sqrt{\sigma_w^2 + \sigma_L^2}}{\sqrt{(\sigma_x^2 + \sigma_w^2)(\sigma_x^2 + \sigma_w^2 + \sigma_L^2)}} \times \exp -\left(t^2/2\sigma_T^2\right), \qquad (18)$$

where I is the peak electron current, e is electron charge, and

$$\sigma_T = \frac{\sigma_z\sqrt{\sigma_x^2 + \sigma_w^2 + \sigma_L^2}}{c\sqrt{\sigma_z^2 + \sigma_x^2 + \sigma_w^2 + \sigma_L^2}} \qquad (19)$$

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Table 1
Electron beam

Energy	32 MeV ($\gamma = 63$)
RMS pulse length (σ_z)	3 ps
Charge/pulse	1.6 nC
Normalized rms emittance	5 mm mrad
Focussed transverse rms width (σ_x)	50 μm

. . .

lasers [6]. The parameters of the equivalent undulator are: $\lambda_u = 0.8$ μm, $B_0 = 500$ T, $K = 3.7 \times 10^{-2}$ and $N_{eff} = 156$. The wavelength of the X-rays generated is peaked at $\lambda_1 = 1$ Å, 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.

. . .

Table 2
Laser beam

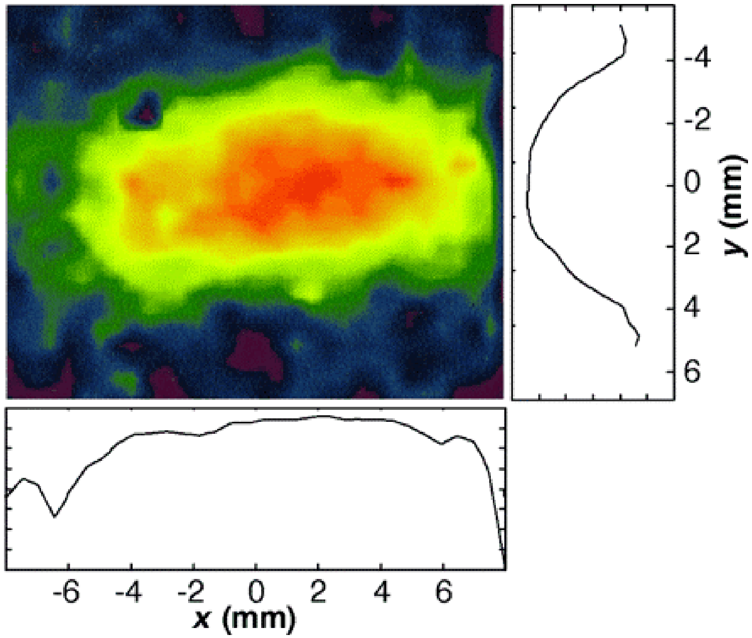
Wavelength (λ_L)	8000 Å
Energy/pulse	0.2 J
RMS pulse length (σ_L/c)	170 fs
Focussed transverse rms width (σ_w)	50 μm
Power density (dP/dA)	3×10^{19} W/m^2

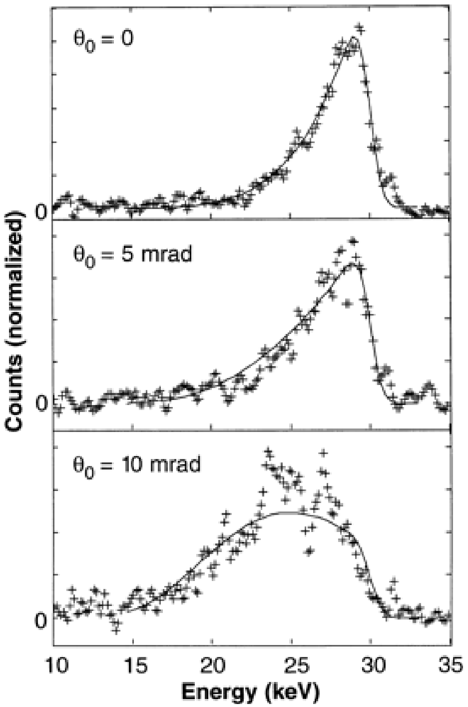
Table 3
Generated X-ray beam

Wavelength (λ_1)	1 Å
RMS pulse length (σ_T)	300 fs
Number of photons ($\Delta\lambda/\lambda = 0.1$)	2.7×10^5
Collection angle (2θ)	2×5 mrad

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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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Laser-Compton scattering from a 20 MeV electron beam

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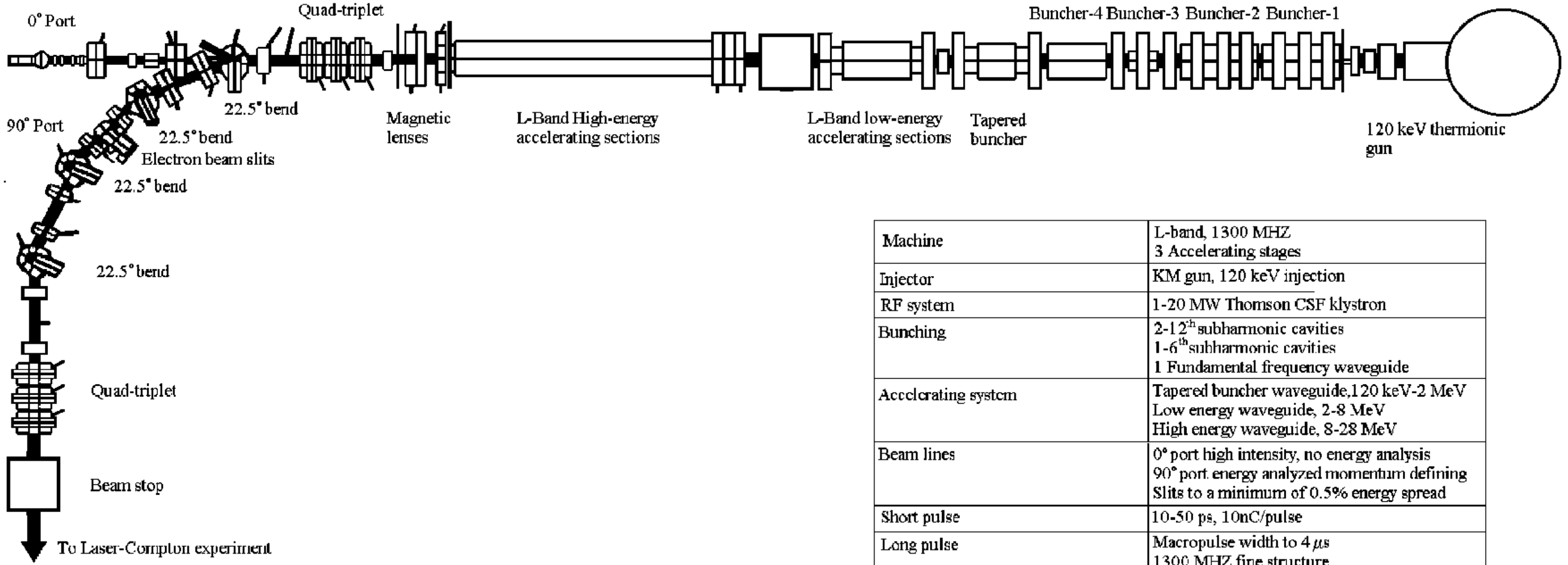
Abstract

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.

PACS: 29.17; 41.75.F; 41.50; 42.60

Keywords: Laser; Compton scattering; X-ray; Linear accelerator

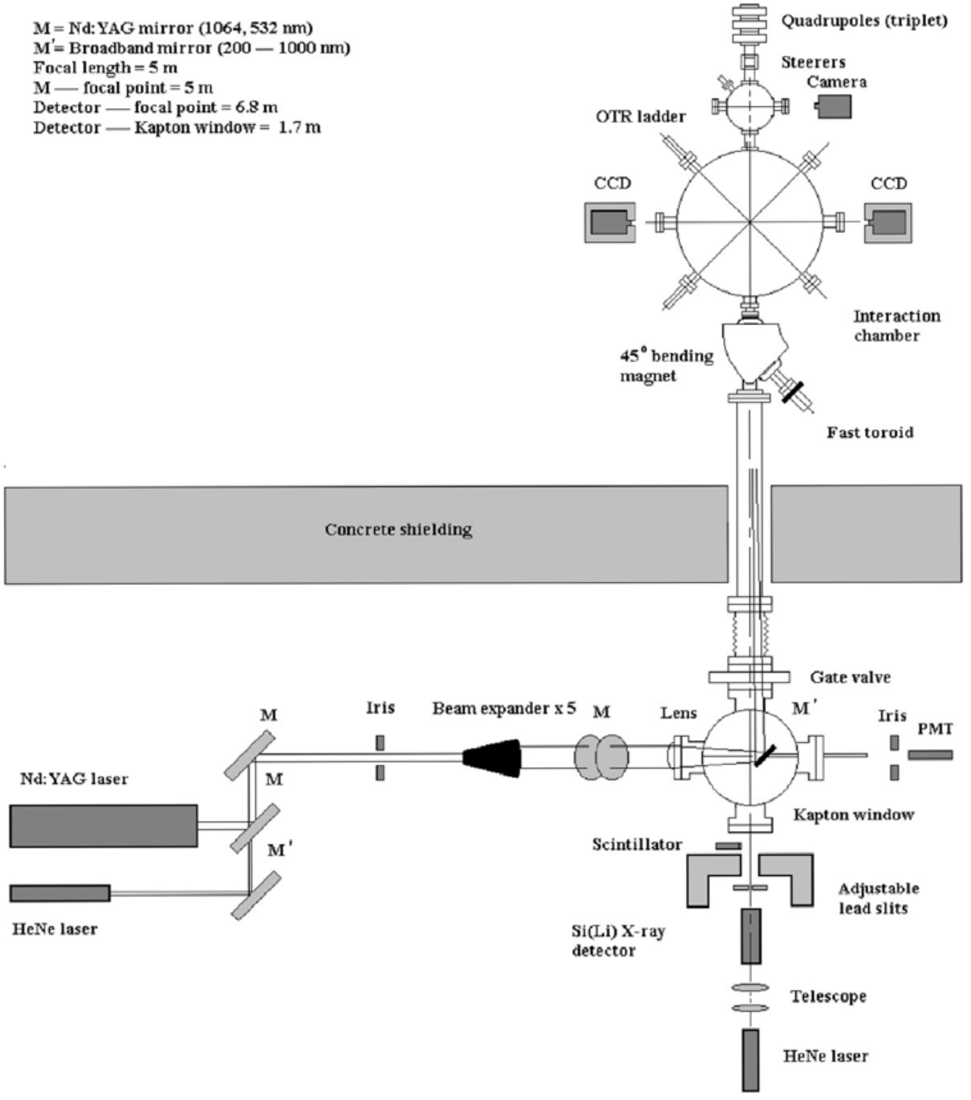
The Layout



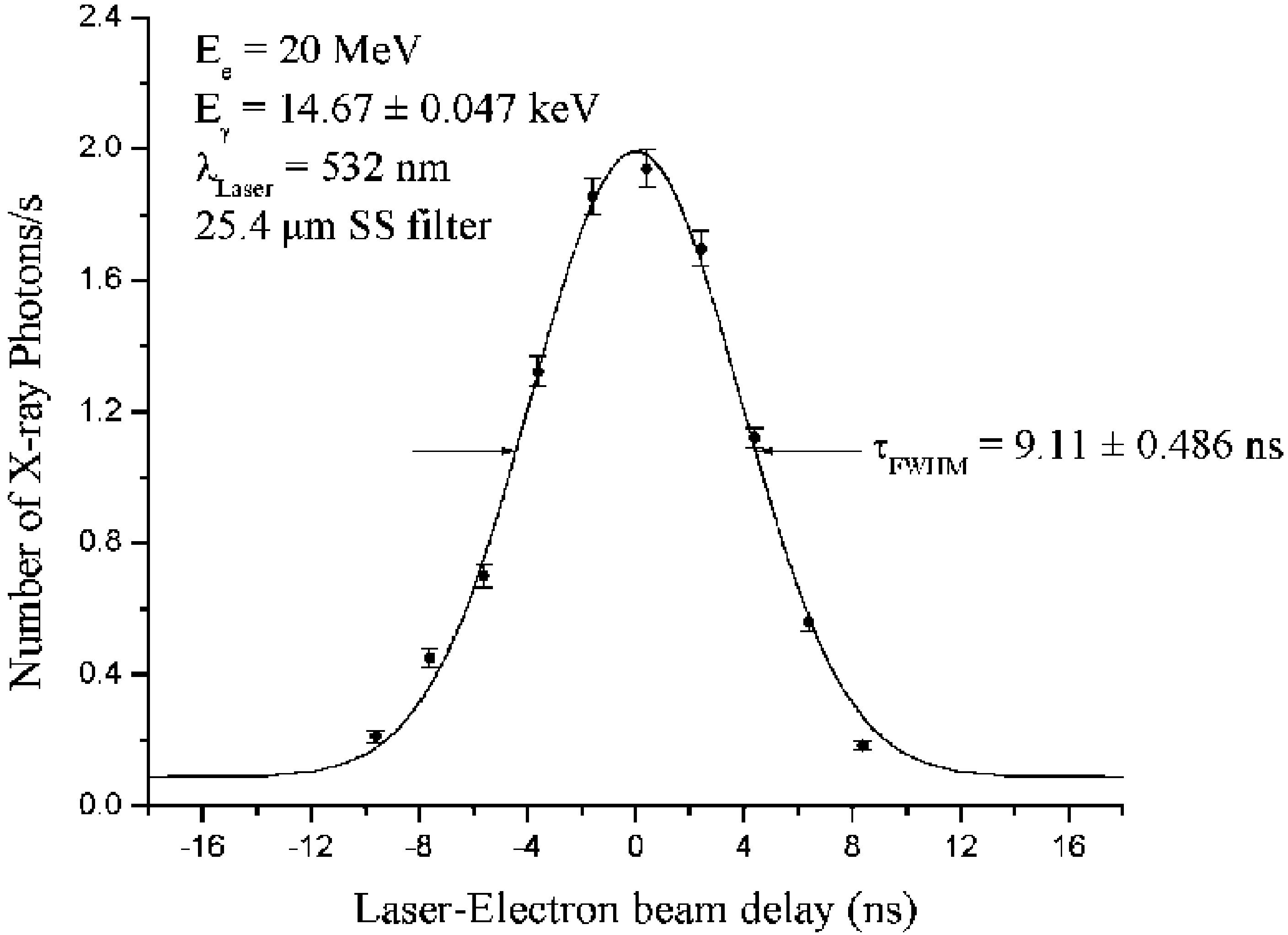
Machine	L-band, 1300 MHZ 3 Accelerating stages
Injector	KM gun, 120 keV injection
RF system	1-20 MW Thomson CSF klystron
Bunching	2-12th subharmonic cavities 1-6th subharmonic cavities 1 Fundamental frequency waveguide
Accelerating system	Tapered buncher waveguide,120 keV-2 MeV Low energy waveguide, 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 outopput at 4 μs wide pulse	2000 nC/macropulse
Spot size	$\sigma_x = 4.77 \pm 0.3\ mm$ $\sigma_y = 2.82 \pm 0.25\ mm$
Emittance	$\varepsilon_x = (14.9 \pm 0.4)\ \pi\ mm\text{-}mrad$ $\varepsilon_y = (10.0 \pm 0.1)\ \pi\ mm\text{-}mrad$

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



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X-ray Measurements

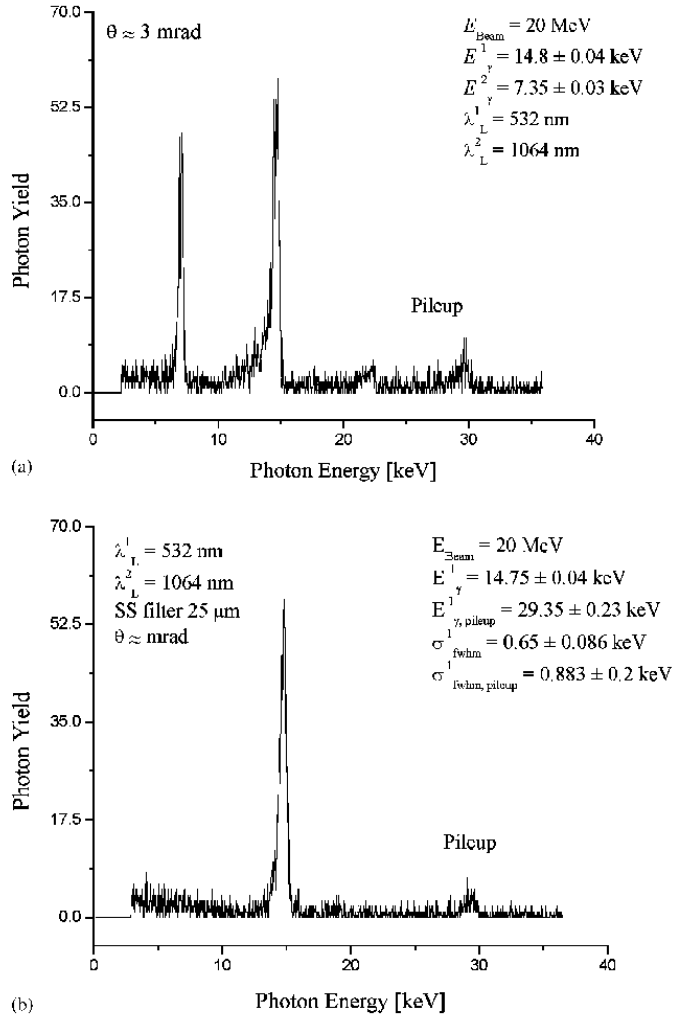

Fig. 6. (a) LCS spectrum from the interaction of electron beam and laser fundamental and second harmonic lines. (b) LCS spectrum using a 25.4 μm SS foil as a high-energy filter.

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 3×10^5 photons/bunch which corresponds to an intensity of $5.6 \times 10^{13}\,s^{-1}$. 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 2×10^{11}.

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

Compact Source of Tunable, Monochromatic, Picosecond X rays

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Plasma Physics Division

M. Baine and S. Ride
University of California at San Diego

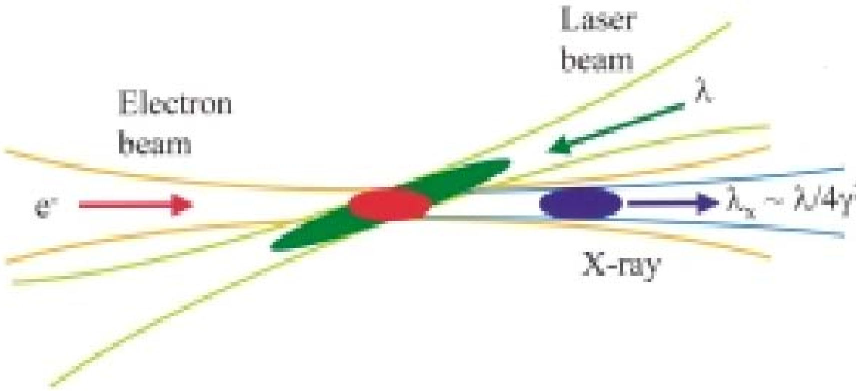

FIGURE 11
ISS interaction configuration.

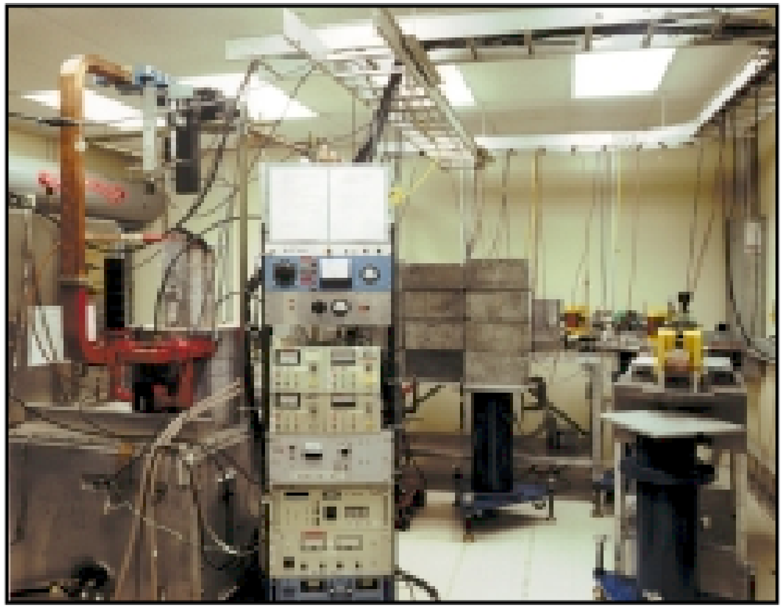

FIGURE 12
The NRL4 MeV RF electron gun beam line. The 20 MW S-band klystron is shown on the left and the electron beam propagates toward the reader on the right.

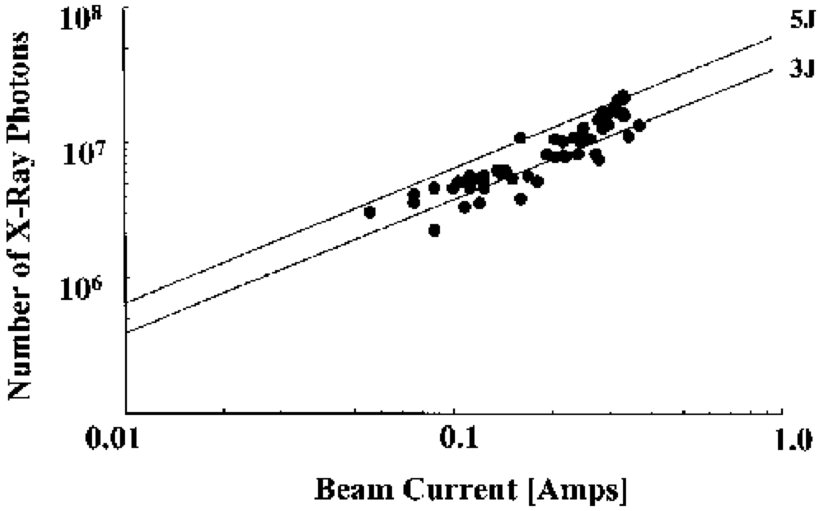

FIGURE 13
Number of x-ray photons generated per pulse as a function of electron beam energy and laser beam energy. The two straight lines indicate the predicted photon numbers for laser beam energies of 3 J and 5 J, respectively.

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PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME **5**, 044701 (2002)

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

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(Received 13 December 2001; published 5 April 2002)

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.

...

and r_e is the classical electron radius. When $\phi \ll 1$ at $\theta = 0$, we have $\phi = (E/E_L)^{1/2}/\gamma$.

...

$\approx 3°$

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

Here $w_0 = 2\sigma_y$ 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.

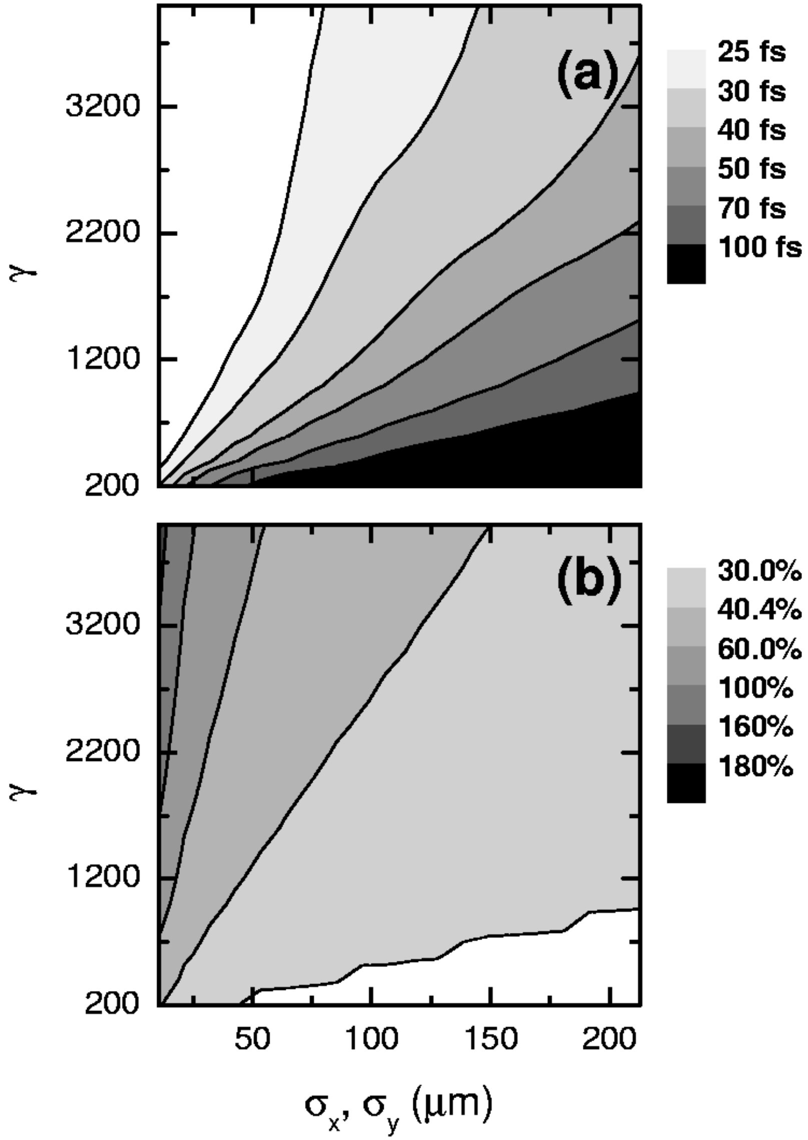

FIG. 1. Contour plots of (a) x-ray pulse FWHM duration in femtoseconds and (b) angle-integrated x-ray FWHM bandwidth $(\Delta E/E)_{\mathrm{int}}$ as a function of transverse bunch size and energy with an rms bunch length of 0.212 ps and a normalized emittance of 10^{-5} mrad. The laser is a 20-fs Ti:sapphire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

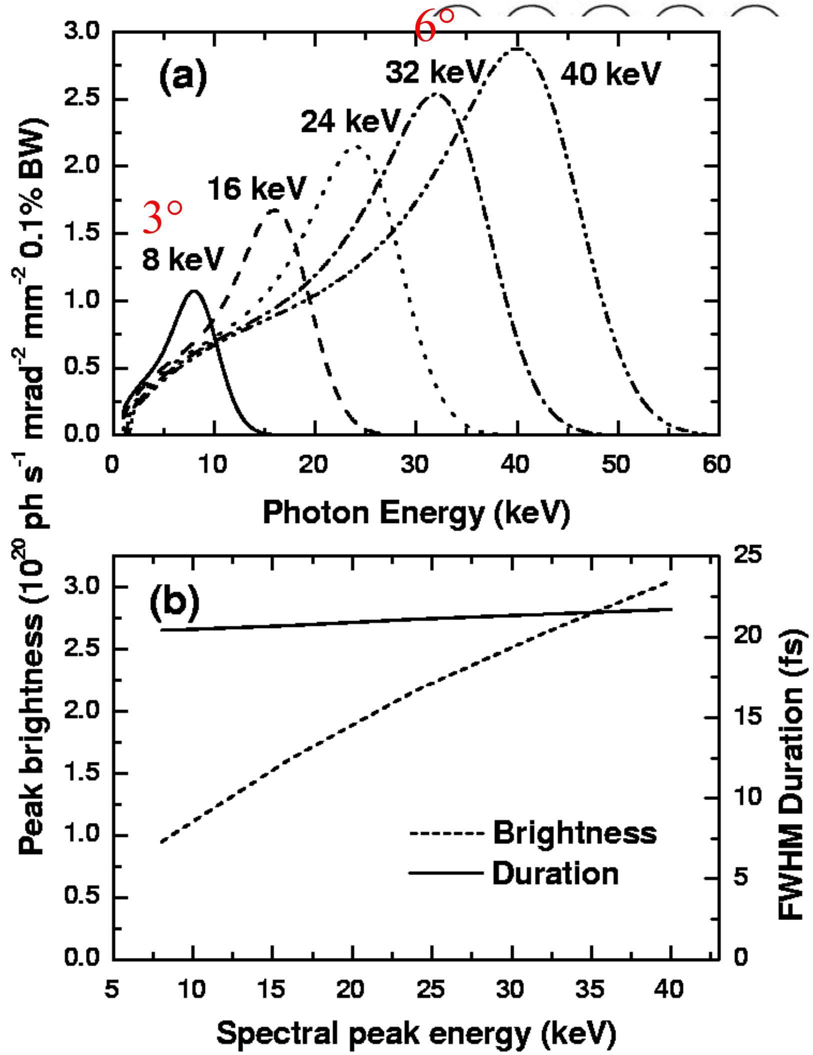

FIG. 3. (a) Spectra with peak positions at 8 to 40 keV and (b) peak brightness (dotted line) and pulse duration (solid line) as a function of the spectrum peak position. The bunch energy is 650 MeV with rms bunch length of 0.212 ps, and the normalized emittance is 10^{-5} mrad. The laser is a 20-fs, 2-J, Ti:sapphire system at 800 nm. Shifting the spectrum peak is accomplished by changing the laser incidence angle.

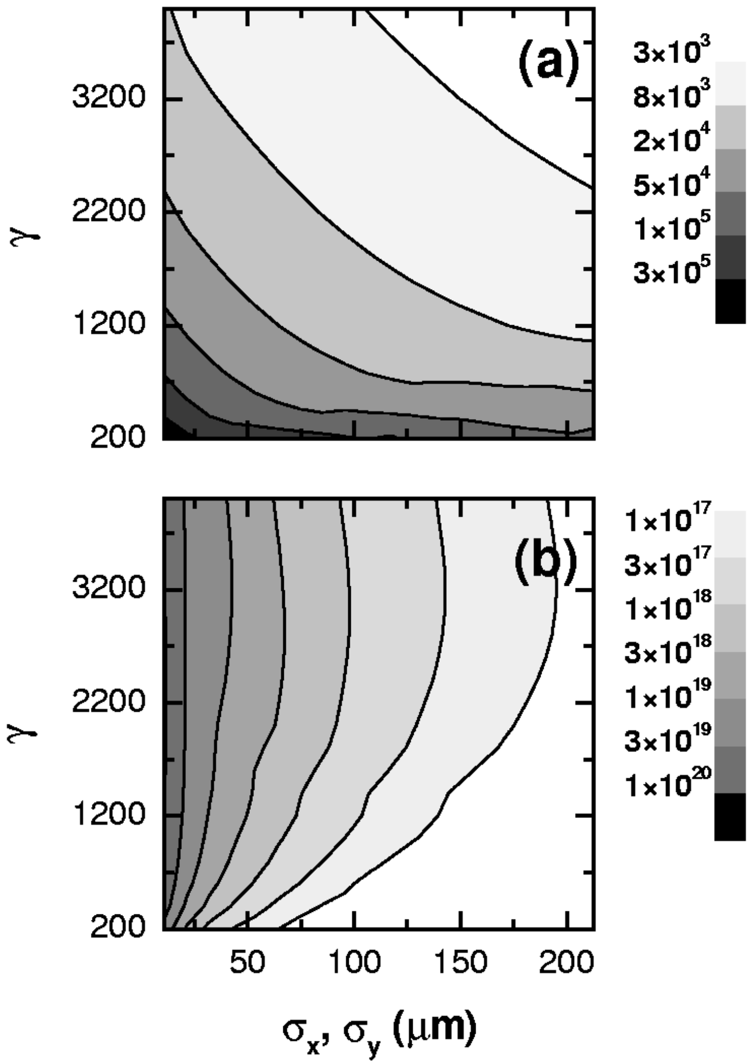

FIG. 2. Contour plots of (a) the average photon flux (photons s^{-1} per 0.1% bandwidth) and (b) the spectral brightness (photons $s^{-1}\,mm^{-2}\,mrad^{-2}$ per 0.1% bandwidth) as a function of transverse bunch size and beam energy. The rms bunch length is 0.212 ps, and the normalized emittance is 10^{-5} mrad. 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.

Jefferson Lab

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electron bunch charge of 1 nC, laser pulse energy of 2 J in a duration of 20 fs [18], the peak brightness obtainable is about 10^{20} photons $s^{-1}\,mm^{-2}\,mrad^{-2}$ per 0.1% BW at 8 keV. The electron beam has a normalized emittance of 10^{-5} mrad and beam energy of 650 MeV ($\gamma \sim 1270$). 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 that of the third-generation synchrotron light sources.

...

intensity is needed. For example, in the calculations in Figs. 2 and 3, for the tightest focus case of $w_0 = 11\ \mu$m,

...

beams are matched in the vertical direction so that the laser beam waist $w_0 = 2\sigma_y$. The pulse duration of the scattered

...

$\beta_{x,\,y} = 4$ mm?

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 I. Summary of the proposed APS SATS X-ray source.

	APS linac[a]	ALS 90 TS[b]	ALS slicing[c]	BNL 180 TS[d]	Laser plasma[e]
Wavelength (Å)	1.5–0.3	0.4	6	1.8	1–10
Repetition rate (Hz)	6	100	10^5		10
Pulse length (fs)	20	300	~100	3500	~300
Average photon flux[e] f	10^6	10^5	10^7	~~10^5~~ 10^4 per 0.1% bw per pulse	10^9
Divergence (mrad)	3	10	0.6		4π
Bandwidth[f]	67%–200%	80%		28%	<0.1%
Peak brightness[g]	~10^{20}	3×10^{15}	~10^{19}	10^{16} (should be 10^{18})	~10^{18}

[a]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.
[b]Reference [6], perspective value.
[c]Reference [11], perspective value.
[d]Reference [8], experimental data.
[e]Reference [10], experimental data.
[f]In photons s^{-1} per 0.1% bandwidth.
[g]In photons s^{-1} mm^{-2} $mrad^{-2}$ per 0.1% BW.

should be 10^{18}

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 $[1 + (ct_j/\sigma_z)^2]^{-1/2}$ for a jitter of t_j 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

Peak brightness alone can be misleading

Single photon peak brightness: $$B_{peak} = \frac{1}{(2\pi)^3 (\hbar/2)^3}$$

or in conventional units:

$$B_{peak}(\text{photon s}^{-1}\text{mm}^{-2}\text{mrad}^{-2}\text{ per 0.1\% bw}) = 2.4\times10^{24}/(\lambda(\text{Å}))^3$$

peak brightness @ 1 Å when photon degeneracy is 1

Summary

Thomson scattering sources can provide ~ $10^{3\text{-}4}$ shorter pulses than that of 3rd generation light sources, with peak brightness lower by at least ~ $10^{3\text{-}4}$ and average flux lower by at least $10^{9\text{-}10}$ 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 ~ $10^{3\text{-}4}$ when compared to a 3rd generation light sources.

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    1. Small-Angle Geometry
    2. **Laser Electron Storage Ring**

VOLUME 80, NUMBER 5 PHYSICAL REVIEW LETTERS 2 FEBRUARY 1998

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

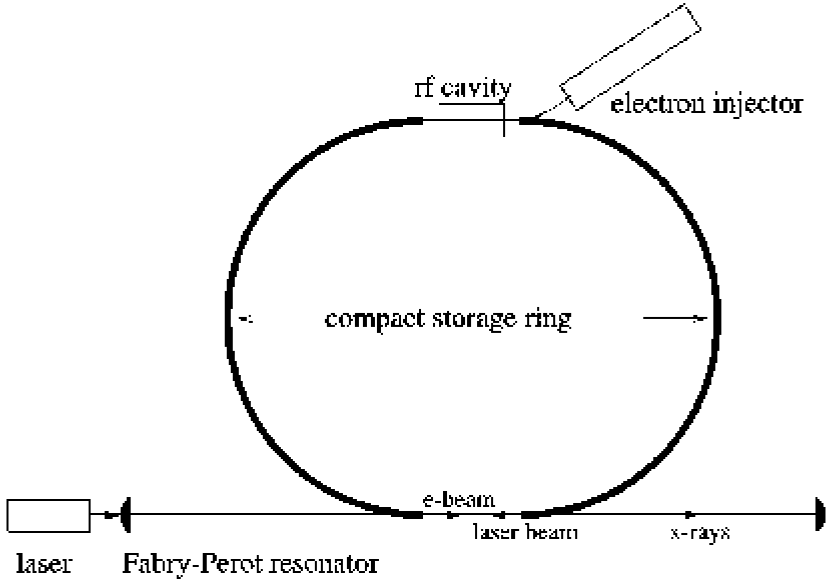

FIG. 1. The schematic diagram of a laser-electron storage ring.

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

$$B_W = \frac{2}{c}\sqrt{2Z_0 I}\,, \qquad (1)$$

where I is the laser intensity, and $Z_0 = (c\epsilon_0)^{-1} = 377\ \Omega$ 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]

$$P_\gamma = \frac{4\pi\epsilon_0}{3} r_e^2 c^3 \gamma^2 B_W^2 = \frac{32\pi}{3} r_e^2 \gamma^2 I\,, \qquad (2)$$

phase space damping rate: $\propto \varepsilon \frac{\langle P_{ph} \rangle}{E}$ $\quad P_{ph} \propto \frac{E^4}{\rho^2}$ due to bends alone, i.e. small

phase space excitation rate: $\propto \frac{1}{E^2}\left\langle \dot{N}_{ph} \left\langle E_{ph}^2 \right\rangle H \right\rangle_{ring}$

Damping From Thomson "Undulator"

the ring, the average damping rate to the normalized transverse emittances $\varepsilon^n_{x,y}$ is given by

$$\Gamma^{\mathrm{RLC}}_{x,y} \equiv -\frac{1}{\varepsilon^n_{x,y}} \left\langle \frac{d\varepsilon^n_{x,y}}{dt} \right\rangle = \frac{1}{n_d T_{\mathrm{rev}}} = \frac{\Delta E_\gamma / E}{T_{\mathrm{rev}}} . \quad (5)$$

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

$$\left\langle \frac{d\varepsilon^n_{x,y}}{dt} \right\rangle_{\mathrm{QE}} = \frac{3}{10} \frac{\lambda_c}{\lambda_L} \frac{(\Delta E)_\gamma}{E} \frac{\beta^*_{x,y}}{T_{\mathrm{rev}}} . \quad (8)$$

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

$$(\varepsilon^n_{x,y})_{\min} = \frac{3}{10}\frac{\lambda_c}{\lambda_L}\beta^*_{x,y}\,. \qquad (9)$$

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

$$\left\langle \frac{d(\sigma_E^2)}{dt} \right\rangle_{QE} = \frac{1}{T_{\mathrm{rev}}}\int_0^{\omega_m} d\omega\,(\hbar\omega)^2\frac{dN_\gamma}{d\omega} = \frac{7}{10}\frac{\hbar\omega_{10}\Delta E_\gamma}{T_{\mathrm{rev}}}\,. \qquad (10)$$

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

$$\frac{1}{\sigma_E^2}\left\langle \frac{d(\sigma_E^2)}{dt} \right\rangle = -2\frac{\Delta E_\gamma/E}{T_{\mathrm{rev}}} \equiv -\Gamma_s^{\mathrm{RLC}}. \qquad (11)$$

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

$$(\sigma_\delta)_{\min} \equiv \left(\frac{\sigma_E}{E}\right)_{\min} = \sqrt{\frac{7}{5}\frac{\lambda_c}{\lambda_L}\gamma}\,. \qquad (12)$$

Note: large initial emittance can hinder the damping

Fabry-Perot resonator & Projected performance

the Fabry-Perot resonators are made of mirrors with total reflectivity $R = 99.99\%$ [finesse $F \simeq \pi/(1-R) \simeq 3.14 \times 10^4$]. To simplify the intrabeam scattering calculations, we consider a round beam for both cases.

laser peak power: 0.2 TW (transient)
6 GW (steady)

rep rate: 0.1 GHz (steady)

laser power req.d: 200 W

TABLE I. Two laser-electron storage ring configurations.

LESR mode	Transient	Steady state
Laser and resonator parameters		
Wavelength [μm]	1	1
Flash energy in the resonator	2 J[a]	20 mJ[b]
Laser pulse length [mm]	3	1
Rayleigh range [mm]	5	8
Focal transverse rms size [μm]	20	25
Electron storage ring parameters		
Energy [MeV]	100	8
Number of electrons	1.3×10^{10}	1.1×10^{10}
Average ring radius [m]	1	0.5
Horizontal/vertical tune	~10	~10
Energy loss per turn	25 keV	1 eV
Trans. damping time	80 μsec	80 msec
Equil. energy spread	2.6%[c]	2.3%[d]
rf frequency [MHz]	2856	1428
rf peak voltage	2 MV	60 KV
Momentum acceptance	15%	23%
rms bunch length [mm]	5.9	6.6
Beta function at IP	1 cm	2 mm
Equil. norm. long. emit. [mm]	31	2.4
Equil. norm. trans. emit. [m]	1×10^{-7}	6×10^{-6}
Max. space charge tune shift	0.012	0.19
X-ray parameters		
Wavelength	6.25 pm	1 nm
Photon energy [keV]	200	1.24
Photon flux [$\sec^{-1}$]	2.6×10^{20}[e]	9.1×10^{14}[f]

[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.