Overview of Compton Scattering Light Sources & Applications

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Overview

• Compton scattering
  – Introduction
  – The case for high energy
  – Physics & modeling
• Technology
  – RF gun & photocathode laser
  – Electron accelerator
  – Interaction laser
• Applications
  – NRF
  – Photo-fission
• Experiments
Compton scattering (1923)

THE

PHYSICAL REVIEW

A QUANTUM THEORY OF THE SCATTERING OF X-RAYS
BY LIGHT ELEMENTS

By Arthur H. Compton

Fig. 1 A  Fig. 1 B
Compton formula
Compton formula

- **Energy-momentum conservation**

\[ u_\mu = \gamma(1, \beta) \quad k_\mu = \left( \frac{\omega}{c}, k \right) \]

\[ u_\mu + \lambda k_\mu = v_\mu + \lambda q_\mu \quad \lambda = \frac{\hbar}{m_0 c} \]

\[
\frac{q}{k} = \frac{\gamma - u \cos \varphi}{\gamma - u \cos \theta + \lambda k \left[ 1 + \cos(\theta - \varphi) \right]}
\]
Tuning and recoil

- 532 nm, head-on collisions, on-axis radiation

\[ \Delta \omega / \omega = 10^{-3} \]

\[ h \nu (\text{MeV}) \]

\[ \gamma \]

\[ \nu T - \nu_c \]

\[ \nu T + \nu_c \]

\[ \omega \]

\[ \text{NRF} \]
Angular correlation
Quick brightness estimate

- Phase space density (on-axis, head-on)
  - Total dose (100%bw)
  - 0.1% bandwidth
  - Pulse duration: e-beam
  - Source size & divergence: geometric emittance

\[ B_x \approx N_e \times QE \times 10^{-3} \times \frac{1}{\Delta \tau} \times \frac{\gamma^2}{\epsilon_n^2} \]

- 0.1 nC, 0.01 photon/e-, 5 ps, 1 mm.mrad, 250 MeV
- 3 x 10^{20} photons/(s x 0.1% bw x mm^2 x mrad^2)
Brightness optimization

\[ \hat{B}_x = \frac{4 \times 10^{-15}}{\pi^2} \frac{\mathcal{E}_0^2 N_e N_A}{e^2 \Delta \tau} \frac{r_0^2}{w_0} \exp \left[ \frac{\chi - 1}{2 \chi \Delta u_{\perp}^2} \left[ 2 + \frac{\delta \omega^2 + \delta \gamma^2 \chi^2}{2 \chi (\chi - 1) \Delta u_{\perp}^2} \right] \right] \left[ 1 - \Phi \left( \frac{\chi - 1}{\sqrt{\delta \omega^2 + \delta \gamma^2 \chi^2}} \left[ 1 + \frac{\delta \omega^2 + \delta \gamma^2 \chi^2}{2 \chi (\chi - 1) \Delta u_{\perp}^2} \right] \right) \right] \]

\times \left[ 1 + \frac{\eta e^{1/\mu^2} (\Phi(1/\eta) - 1) - \mu e^{1/\mu^2} (\Phi(1/\mu) - 1)}{\mu^2 - \eta^2} \right],

where we have made the approximation \( \Delta u_{\perp} r_b = \varepsilon u_0 / \gamma_0 \approx \varepsilon. \)

![Graph showing the relationship between beam radius (µm, rms) and photons per cm² x mrad² x 0.1% bw.](image)
The case for high energy

- Brightness scales as $\gamma^2 / \varepsilon_n^2$
- Scattering cross-section is essentially energy-independent
- Quantum efficiency depends on interaction geometry (beams overlap)
- Photon energy roughly scales as $\gamma^2$
- Source efficiency can be high (%), even compared to SASE FEL
- Example: 250 MeV electrons, 2.2 MeV photons
Compton scattering light sources

• 1923 Compton scattering

• 1928 Linac
  – Widerøe, Rolf Archiv Elektronik und Uebertragungstechnik 21: 387 (1928)

• 1939 Klystron
Compton scattering light sources

- 1960 Laser

- 1965 First experiments using a laser
Compton scattering light sources

- 1985 CPA

- 1989 RF Gun

- Emittance compensation (Bruce Carlsten)
Laser/electron beam collisions

Frame Parameters:
- $x$ $\pm 100 \mu m$
- $y$ $\pm 100 \mu m$
- $z$ $\pm 1.2 \text{ mm } \pm 4 \text{ ps}$

Animation/Simulation by Fred V. Hartmann & Winthrop J. Brown

TIMEFRAME = 4 ps
Modeling

• 3 main approaches:
  – Differential scattering cross-section
  – Radiation integral (Thomson scattering)
  – Monte Carlo simulations
Differential scattering cross-section

- **Method:** incoherently sum discrete e-/photon interactions over laser and electron beam phase spaces
- **Pros:**
  - Recoil properly accounted for
  - Spin & magnetic corrections can be included
- **Cons:**
  - Nonlinear interactions much harder to describe
  - Laser phase space correlations require Wigner function formalism
Radiation integral

- **Method:** Fourier transform e- trajectories

\[
\frac{d^2 N}{dq d\Omega} = \frac{\alpha}{4\pi^2} q \left| \int_{-\infty}^{+\infty} \pi_{\mu} u^{\mu} e^{-iq_{\nu}x^\nu} d\tau \right|^2
\]

- **Pros:**
  - Readily accounts for diffraction, pulse chirp and other incident laser phase space correlations
  - Easily extended to include nonlinear effects

- **Cons:**
  - Does not include recoil
  - Cross-section is valid for low-energy, no spin
Thomson scattering

• Radiation formula

\[
\frac{d^2N}{dq d\Omega} = \frac{\alpha}{4\pi^2} q \left| \int_{-\infty}^{+\infty} \pi^\mu u^\mu e^{-i q \cdot x} \, d\tau \right|^2
\]

• Use phase as independent variable

\[
\frac{d^2N}{dq d\Omega} = \frac{\alpha}{4\pi^2} \frac{q}{\kappa^2} \left| \pi^\mu \int_{-\infty}^{+\infty} u^\mu (\phi) e^{-i q \cdot \phi} \frac{\int u^\nu \, d\psi}{\kappa} \, d\phi \right|^2
\]
Thomson scattering

- Light cone variables (Feynman)

\[ \kappa = u_\mu^0 k^\mu, \quad \lambda = u_\mu^0 q^\mu \]
\[ \kappa - \lambda = \xi k_\mu q^\mu \]

- Electron trajectory (ballistic + linear oscillation)

\[ u_\mu = u_\mu^0 + A_\mu - k_\mu \frac{A^v u_0^v}{k_v u_0^v}, \quad x_\mu - x_\mu^0 = \frac{u_\mu^0}{\kappa} \phi \]
Thomson scattering

- 4-polarization

\[
\epsilon_\mu = \frac{1}{\sqrt{-A_v A^v}} \left( A_\mu - k_\mu \frac{A_v u_0^v}{k_v u_0^v} \right), \quad \epsilon_\mu \epsilon^\mu = -1
\]

- Radiation spectrum

\[
\frac{d^2N}{dq d\Omega} = \frac{\alpha}{4\pi^2 \kappa^2} \frac{q}{\lambda^2} A_0^2 \left| e^{-i q \cdot x_0} \right|^2 \left| \pi_\mu \epsilon^\mu \right|^2 \left| \int_{-\infty}^{+\infty} e^{i \phi \left( 1 - \frac{1}{\kappa} \right)} d\phi \right|^2
\]

- Fourier transform of delta-function
- Identical to Compton formula, but no recoil
Klein-Nishina cross-section

- Spin-independent component

\[
\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2} \left( \frac{q}{\kappa} \right)^2 \left\{ \frac{1}{2} \left( \frac{\kappa + \lambda}{\lambda} \right) - 1 \right. \\
+ 2 \left[ \varepsilon_\mu \pi^\mu - \frac{(\varepsilon_\mu u^\mu)(\pi_\mu v^\mu)}{\kappa} + \frac{(\varepsilon_\mu v^\mu)(\pi_\mu u^\mu)}{\lambda} \right]^2 \right\}
\]
Klein-Nishina cross-section

- For large values of recoil, the cross-section deviates from the Thomson scattering dipole

\[ \gamma_0 = 0 \]
\[ k\lambda_C = 0, \ 0.5, \ 1.0 \]
Compton/Thomson comparison

- **Compton formula limit**
  \[ \kappa - \lambda = \lambda \kappa \mu q^\mu \rightarrow \kappa = \lambda \]

- **Energy-momentum limit**
  \[ u_\mu + \lambda k_\mu = v_\mu + \lambda q_\mu \rightarrow u_\mu = v_\mu \]

- **Cross-section limit**
  \[
  \frac{d\sigma}{d\Omega} = \left( \frac{q}{\kappa} \right)^2 \left\{ \frac{1}{2} \left( \frac{\kappa + \lambda}{\lambda + \kappa} \right) - 1 \right\} + 2 \left[ \left( \varepsilon_\mu u^{\mu} \right) \left( \pi_\mu v^{\mu} \right) \frac{1}{\kappa} + \left( \varepsilon_\mu v^{\mu} \right) \left( \pi_\mu u^{\mu} \right) \frac{1}{\lambda} \right]^2 \]
\]
Adding recoil to Thomson scattering

• Motivation
  – The cross-section differences between Thomson and Compton scattering are a higher-order perturbation in $\hbar$ than the frequency shift due to recoil
  – Recoil becomes significant (%) for MeV photons

• Approach
  – Add the appropriate correction term for plane waves in the linear regime
  – Generalize
Plane wave

- Modify electron trajectory

\[ u_\mu = u^0_\mu + A_\mu - k_\mu \frac{A_\nu u^\nu_0}{k_\nu u^\nu_0} + \lambda k_\mu \]

\[ x_\mu - x^0_\mu = \left( \frac{u^0_\mu + \lambda k_\mu}{\kappa} \right) \phi \]

- Radiation integral contains recoil term

\[ \frac{d^2N}{dq d\Omega} = \frac{\alpha}{4\pi^2} \frac{q}{k^2} A^2_0 \left| e^{-iq_\nu x^\nu_0} \right|^2 \left| \pi_\mu \epsilon^\mu \right|^2 \left[ \int_{-\infty}^{+\infty} e^{i\phi} \left( 1 - \frac{\lambda + \lambda q_\nu k^\nu}{\kappa} \right) d\phi \right] \]

\[ \kappa - \lambda = \lambda k_\mu q^\mu \]
Nonlinear radiation phase

- **Plane wave**

\[
q^\mu x_\mu = q^\mu x^\mu_0 + \frac{1}{\kappa} \left\{ \phi \left[ \lambda + k_\mu q^\mu \left( \hat{\lambda} n + \frac{\langle -A_v A^v \rangle}{2\kappa} \right) \right] + \cos \phi A_0 \left( \frac{u^0_v a^v}{\kappa} a_\mu - k_\mu \right) q^\mu \right. \\
\left. + \sin \phi A_0 \sigma \left( \frac{u^0_v b^v}{\kappa} b_\mu - k_\mu \right) q^\mu + \sin 2\phi \frac{k_\mu q^\mu}{2\kappa} \frac{\sigma^2 - 1}{4} \right\}
\]

- **Resonance (periodicity)**

\[
\frac{q^\mu_n}{\kappa} \left( u^0_\mu + \hat{\lambda} n k_\mu + \frac{k_\mu}{2\kappa} \langle -A_v A^v \rangle \right) = n
\]
Compare with nonlinear Compton

• **Energy-momentum conservation**

\[ u_\mu + \hat{\lambda}_C \left( k^1_\mu + k^2_\mu + \ldots + k^n_\mu \right) = v_\mu + \hat{\lambda}_C q^n_\mu \]

• **Incident wave is coherent**

\[ k^1_\mu = k^2_\mu = \ldots = k^n_\mu \]

• **Replace velocity by nonlinear solution**

\[
\begin{align*}
\left( u^0_\mu + A^\nu_\mu - k^\nu_\mu \frac{A^\nu_\nu A^\nu_\nu + 2u^0_\nu A^\nu_\nu}{2u^0_\nu k^\nu_\nu} \right) & \left( nk_\mu - q^n_\mu \right) = \hat{\lambda} n k_\mu q^n_\mu \\

nu^0_\mu k^\mu - \left( u^0_\mu - \frac{k^\mu_\mu}{2u^0_\nu k^\nu_\nu} \langle A^\nu_\nu A^\nu_\nu \rangle \right) q^n_\mu &= \hat{\lambda} n k_\mu q^n_\mu
\end{align*}
\]
Nonlinear Compton formula

- Nonlinear Compton scattering frequency
  - Nonlinear radiation pressure
  - Multi-photon recoil

\[ n\kappa - \lambda = k_\mu q_\mu^n \left( n\hat{\lambda} + \frac{\langle -A_v A_v^\dagger \rangle}{2\kappa} \right) \]

- Nonlinear radiation pressure
  - Scales as \( A_0^2 \Delta \phi \)

\[ \frac{d^2N}{dq dq'd\Omega} = \frac{\alpha}{4\pi^2} \frac{\chi}{k} \Bigg| A_0 e^{i\chi A_0^2 \Delta \phi} \int_{-\infty}^{\infty} \frac{x \sin \phi + y \cos \phi}{\cosh (\phi / \Delta \phi)} \exp \left\{ i\chi \left[ \phi (1 + r) + A_0^2 \Delta\phi \tanh \left( \frac{\phi}{\Delta \phi} \right) \right] \right\} d\phi \Bigg|^2 \]
Nonlinear effects

- Low-intensity: inhomogeneous radiation pressure, dressed electron mass
- High-intensity: harmonic production, multi-photon effects
- Synchrotron-like radiation (projection of the linear oscillation component along the direction of observation)
3D trajectories
3D nonlinear spectra

![Graphs showing 3D nonlinear spectra]
Interaction probability vs. spectral purity

• The interaction probability and the radiation pressure dephasing scale identically

\[
\frac{dN}{d\tau} = \sigma c \frac{u_\mu k^\mu}{\gamma k} n_\lambda \left[ r_v(\tau) \right] \quad n_\lambda \propto A_0^2
\]

\[
\frac{d^2N}{dq d\Omega} = \frac{\alpha}{4\pi^2} \frac{q}{\kappa^2} \left| \pi_\mu \left( \int_{-\infty}^{+\infty} u^\mu(\phi) e^{-i\Phi} d\phi \right) \right|^2
\]

\[
\Phi = \frac{\phi}{\kappa} \left( q_\mu u_0^\mu + \lambda q_\mu k^\mu \right) + \frac{q_\mu k^\mu}{2\kappa^2} A_0^2 \int_{-\infty}^{+\infty} g^2(\psi) \left( \sin^2 \psi + \sigma^2 \cos^2 \psi \right) d\psi
\]

• Rule of thumb: \( A_0^2 \approx \Delta \phi \approx \frac{1}{k_0^2 w_0^2} \)
3D nonlinear spectra + electron beam phase space
Nonlinear Thomson scattering of intense laser pulses from beams and plasmas

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Nonlinear Thomson scattering: A tutorial

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Nonlinear effects

FIG. 2. The normalized intensity, as a function of normalized frequency $\omega/4\gamma^2\omega_0$ and angle $\gamma_0\theta$ in the $\phi=0$ plane, of the radiation scattered by a relativistic electron ($\gamma_0=5$) from a counterpropagating, linearly polarized laser pulse ($N_0=7$). (a) shows the first two harmonics for $a_0=0.5$ and (b) shows the first three harmonics for $a_0=1.0$. 
Typical experimental setups

Electron source
- Thermionic
- Field emission
- Photo-emission
- Plasma

Accelerator
- Warm rf
- SC
- Electrostatic
- Laser wakefield

Radiator
- Laser
- FEL

Re-circulation
- Storage ring
- ERL
- Cavity
- RING
Technology

- Example: 2 MeV source for NRF
- RF gun
- Photocathode laser
- Electron accelerator
- Interaction laser
- 5-10 year challenges
System Overview

• RF gun: 5.59 cells, 11.424 GHz, 200 MV/m
• Photocathode laser: Fiber-based, 4^{th} harmonic, 50 uJ
• Linac: 250 MeV, 11.424 GHz, > 75 MV/m
• Interaction laser: 0.5 J, 1.064 nm, 10 ps; 0.1 J, 2\omega
• Nominal rep. rate: 60-120 Hz
• Dose: 10^7-10^8/shot
• Flux: 10^{10}/s
• Energy range: 0.5 – 2.2 MeV
• Spectral bandwidth: 0.5%
5.59 Cell X-band RF gun

- Cathode electric field: 200 MV/m
- Bunch duration: $10^\circ$ 2.5 ps
- Injection phase: optimized for each geometry; $20^\circ$ for 5.59-cells
- Charge: 250 pC
- Emittance: as low as 0.18 mm.mrad
400 MW 11.424 GHz RF power

- The requirements on rf phase and amplitude stability are very stringent
- $1^\circ$ rf phase (243 fs), 0.1%
- ScandiNova solid-state modulators
- SLAC XL-4 klystrons + SLED-II
X-Band RF power distribution

2 X 50 MW Klystrons
(1.5 μs Pulses)

450 kV, 700 A
1.5 μs, 120 Hz
Modulator

100 MW
1.5 μs

400 MW
0.25 μs

SLED-II Delay Lines

RF distribution to photoinjector and
accelerator structures

X-band photoinjector

Six T53VG3MC SLAC accelerator sections,
capable of accelerating electrons to 250 MeV
250 MeV X-band linac
Sub-picosecond timing

**Lasers:**
- Oscillator
- Phase Lock Crystal
- PDL
- 40.8 MHz
- 81.6 MHz
- 10 kHz
- 10 kHz
- 120 Hz
- 20 pulses 12.25 ns apart
- 20 pulses 12.25 ns apart
- RF
- 11.424 GHz
- PDRO
- TWA
- Klystron
- Re-circulation

**Electron Beam:**
- Klystron (120 Hz)
- 50 MW
- 200 MW
- 250 ns
- 250 MeV
- 20 pulses x 0.4 nC
- 1 mm mrad
- 0.1% 
- 4 ps
- 20 pulses (0.4 nC)
- 12.25 ns apart
- GUN
- Traveling wave
- Output
- SLED
- 1.6 μs
- 400 ns
The 1-J 120-Hz Injection Laser (HIL) is a relay-imaged master oscillator power amplifier based on commercial diode pumped amplifier heads.
ILS compressor & SHG
Applications

- Ultrafast x-ray diffraction
  - Ron Ruth, Lyncean
  - Frank Caroll et al., MXI
- Medical x-rays
- Protein crystallography
  - Ron Ruth, Lyncean
- Pulsed positrons
- NRF
- Photo-fission
NRF mission space
T-REX key properties

T-REX is a 0.1 - 0.9 MeV source

$10^6$ photons/s

$6 \times 10 \text{ mrad}^2$

$\sim 10\%$ bandwidth
Nuclear resonance fluorescence

- Isotopic sensitivity
- Large cross-sections
- Narrow bandwidth (~10^{-6})
- Bertozzi detection method
Direct detection of $^7\text{LiH}$ behind Pb

- LN$_2$-cooled HPGe
Indirect detection of $^7\text{LiH}$

- Observation of resonant attenuation of gamma-rays in the transmitted beam
- Low false positive/negative rate

Diagram:
- Interrogated sample (movable)
- Shielding
- Reference “notch” detector
- Bertozzi method
- HPGe detectors
Target material present

- No NRF Detected
- Resonant photons absorbed by interrogated sample
Target material absent

- NRF detected
High-Energy Photons from Compton Scattering of Light on 6.0-GeV Electrons*

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Compton scattering of optical photons on 6.0-GeV electrons has been observed at the Cambridge Electron Accelerator. A giant-pulsed ruby-laser burst of 0.2 J, impinging upon a 2-mA circulating electron current, was observed to yield about 8 scattered photons per pulse. These photons acquire, through a twofold Doppler shift, energies of hundred of MeV, and are expected to retain to a high degree the polarization of the laser beam. The observed yield is compatible with predictions based upon the theory of Compton scattering.
Fig. 6. Čerenkov-counter pulse-height distributions. Laser-correlated pulses are associated with second laser pulse. (2.3 units = 3 GeV).
Thomson Backscattering from a Relativistic Electron Beam as a Diagnostic for Parallel Velocity Spread

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(Received 16 November 1983)

Thomson backscattering of CO$_2$-laser radiation is used to determine the parallel momentum spread of a 1.8-kA/cm$^2$, 700-kV magnetized electron beam, emitted from a cold cathode in an apertured diode. The beam is found to be suitable for Raman free-electron-laser applications: a normalized momentum spread of $(0.6 \pm 0.14)$% was obtained for the inhomogeneous broadening; it is also found that the use of an undulator will cause an increase of the broadening.
Observation of 20 eV x-ray generation in a proof-of-principle laser synchrotron source experiment

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(Received 12 December 1994; accepted for publication 13 March 1995)

A laser synchrotron source (LSS) [P. Sprangle, A. Ting, E. Esarey, and A. Fisher, J. Appl. Phys. 72, 5032 (1992)] was proposed to generate short-pulsed, tunable x rays by Thomson scattering of laser photons from a relativistic electron beam. A proof-of-principal (p.o.p.) experiment on this LSS configuration is performed. An intense laser pulse (λ₀=1.053 μm) is Thomson backscattered from a focused relativistic electron beam. Time integrated x-ray signals from a photocathode/electron multiplier, at an electron beam energy of 650 keV and an x-ray photon energy of 20 eV, indicate an increase in the x-ray signals above the baseline by an amount comparable to the theoretically predicted value. © 1995 American Institute of Physics.
FIG. 3. X-ray signals from p.o.p. LSS experiment.
Tunable X-Ray Generation in a Free-Electron Laser by Intracavity Compton Backscattering

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(Received 27 June 1996)

A nearly monochromatic x-ray beam of 7 to 12 keV has been produced with an infrared free-electron laser (FEL). This is achieved when the intense laser field generated and stored in the laser optical cavity is backscattered by the FEL relativistic electron beam. [S0031-9007(96)01352-X]

![Graph showing X-ray detector signal with laser on and off. The background is due to lost electrons and has the time structure of the electron beam.](image)
Femtosecond X-ray Pulses at 0.4 Å Generated by 90° Thomson Scattering: A Tool for Probing the Structural Dynamics of Materials


Pulses of x-rays 300 femtoseconds in duration at a wavelength of 0.4 angstroms (30,000 electron volts) have been generated by 90° Thomson scattering between infrared terawatt laser pulses and highly relativistic electrons from an accelerator. In the right-angle scattering geometry, the duration of the x-ray burst is determined by the transit time of the laser pulse across the ∼90-micrometer waist of the focused electron beam. The x-rays are highly directed (∼0.6° divergence) and can be tuned in energy. This source of femtosecond x-rays will make it possible to combine x-ray techniques with ultrafast time resolution to investigate structural dynamics in condensed matter.
X-Ray Based Subpicosecond Electron Bunch Characterization Using 90° Thomson Scattering


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X rays produced by 90° Thomson scattering of a femtosecond, near infrared, terawatt laser pulse of a 50 MeV electron beam are shown to be an effective diagnostic to measure transverse and longitudinal density distributions of an electron beam (e beam) with subpicosecond time resolution. The laser beam was focused onto the e-beam waist, generating 30 keV x rays in the forward direction. The transverse and longitudinal e-beam structures have been obtained by measuring the intensity of the x-ray beam, while scanning the laser beam across the e beam in space and time. The e-beam divergence has been obtained through measurement of spatial and spectral characteristics of the scattered x-ray beam.

[S0031-9007(96)01621-3]
FIG. 1. Schematic of the experimental setup.

FIG. 3(color). (a) False color CCD image of the spatial profile of a 30 keV x-ray pulse on the phosphor screen, which is located 80 cm from the IP; (b) ■ (square) — horizontal line profile and fitting curve (solid line), ▲ (triangle) — vertical line profile and fitting curve (dashed line) from (a). The scale has been converted into angular units.
Observation of Nonlinear Effects in Compton Scattering

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Nonlinear Compton scattering has been observed in the collision of a low-emittance 46.6-GeV electron beam with terawatt pulses from a Nd:glass laser at 1054 and 527 nm wavelengths in an experiment at the Final Focus Test Beam at SLAC. Peak laser intensities of $10^{18}$ W/cm² have been achieved, corresponding to a value of 0.6 for the parameter $\eta = eE_{\text{rms}}/m\omega_0c$. Results are presented for multiphoton Compton scattering in which up to four laser photons interact with an electron, in agreement with theoretical calculations. [S0031-9007(96)00012-9]
FIG. 4. Energy spectra of scattered electrons as observed in the ECAL calorimeter. (a) Data and simulation for 42-mJ infrared laser pulses. (b), (c) Data (open and filled-in circles) and simulations (solid curves) for infrared (b) and green (c) laser pulses, scaled to standard values of the interaction geometry. The dashed lines show the simulation for multiple linear Compton scattering only.
Positron Production in Multiphoton Light-by-Light Scattering

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A signal of 106 ± 14 positrons above background has been observed in collisions of a low-emittance 46.6 GeV electron beam with terawatt pulses from a Nd:glass laser at 527 nm wavelength in an experiment at the Final Focus Test Beam at SLAC. The positrons are interpreted as arising from a two-step process in which laser photons are backscattered to GeV energies by the electron beam followed by a collision between the high-energy photon and several laser photons to produce an electron-positron pair. These results are the first laboratory evidence for inelastic light-by-light scattering involving only real photons. [S0031-9007(97)04008-8]
FIG. 1. Schematic layout of the experiment.

FIG. 4. Dependence of the positron rate per laser shot on the laser field-strength parameter $\eta$. The line shows a power law fit to the data. The shaded distribution is the 95% confidence limit on the residual background from showers of lost beam particles after subtracting the laser-off positron rate.
Nonlinear Thomson scattering, Umstadter et al. (1998)
Demonstration of $8 \times 10^{18}$ photons/second peaked at 1.8 Å in a relativistic Thomson scattering experiment

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$7.6 \times 10^6$ 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.
FIG. 1. (Color) Principle diagram of the CO$_2$ LSS experiment.

FIG. 10. Typical scope traces of the x-ray signal (at 100 mV/div) and noise (at 50 mV/div).
Observation of high-intensity X-rays in inverse Compton scattering experiment

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Abstract

We report the first results of high-intensity X-ray generation using Inverse Laser Compton scattering. This experiment was carried out by a US–Japan collaboration at the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF) in September 1999. The 3.5 ps X-ray pulse at 6.5 keV, containing $3 \times 10^6$ X-ray photons was generated by the interaction of 60 MeV, 0.5 nC electron bunches and CO$_2$ laser pulses of 600 MW peak power. © 2000 Elsevier Science B.V. All rights reserved.

\textbf{PACS:} 13.60.Fz; 41.60.Ap; 41.75.Ht; 42.55.Lt; 42.81.Wg

\textbf{Keywords:} CO$_2$ laser; Compton scattering; X-rays; Electron beam
### Table 1
Electron beam and CO₂ laser parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electron bunch</strong></td>
<td></td>
</tr>
<tr>
<td>Beam energy</td>
<td>60 MeV</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>0.5 nC</td>
</tr>
<tr>
<td>Bunch length</td>
<td>3.5 ps</td>
</tr>
<tr>
<td>Beam size at focus point ($σ_x/σ_y$)</td>
<td>40/40 μm</td>
</tr>
<tr>
<td><strong>CO₂ laser</strong></td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td>10.6 μm</td>
</tr>
<tr>
<td>Energy/pulse</td>
<td>200 mJ</td>
</tr>
<tr>
<td>Pulse length (FWHM)</td>
<td>180 ps</td>
</tr>
<tr>
<td>Beam size at focus point ($σ_x/σ_y$)</td>
<td>40/40 μm</td>
</tr>
</tbody>
</table>

29 Sep 1999
Compact X-ray sources by intense laser interactions with beams and plasmas

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Abstract

Short pulsed X-rays have been experimentally generated by 90° Thomson scattering of 2TW, 90fs laser pulses by 17MeV electron beams. A few 100fs X-ray pulses have been generated via backward Thomson scattering from a few 100fs electron bunches made by a bunch compression chicane. Soft X-ray may be generated via laser-plasma nonlinear Thomson scatterings as a source of X-ray microscope. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 34.80.Q

Keywords: Short pulse X-ray; T³ laser; Thomson scattering; Bunch compression chicane; Laser-plasma interaction
Fig. 2. X-ray signals observed as a function of the time delay between laser and electron pulses.
Short-Pulse X-Ray Generation via Thomson Scattering in 0° and 90° Interactions

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Short-pulse X-ray generation was demonstrated in a scattering experiment between a 4 ps electron beam and a 10 ps Nd:YLF laser beam. The beams interacted at 0° and 90°. The X-ray signal was measured using a microchannel plate. Maximum X-ray energy was analytically estimated to be 3.55 keV in the 0° interaction and 1.77 keV in the 90° interaction with a pulse duration of 4 ps for both interactions. Measured X-ray intensities exhibited good linearity with the incident laser light pulse energy for both scattering configurations. The measured X-ray intensity was compared with the intensity analyzed from the beam sizes and energies of both beams. The intensities matched and were of the order of $10^9$ photons in the 0° interaction.

KEYWORDS: Thomson scattering, Compton scattering, laser synchrotron, short-pulse X-ray, RF photocathode, short-pulse laser
Fig. 5. Observed MCP signal. Background signal was mainly caused by UV light scattered at the surface of the photocathode.
Tunable Monochromatic X Rays: A New Paradigm in Medicine

Frank E. Carroll

Fig. 3.—Panoramic picture of machine shows accelerator as long rectangular structure in background. Table terawatt laser is spread out over optical table in foreground.
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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PACS: 29.17, 41.75.F; 41.50; 42.60

Keywords: Laser; Compton scattering; X-ray; Linear accelerator
M = Nd:YAG mirror (1064, 532 nm)
M′ = Bremsstrahlung mirror (200 — 1000 nm)
Focal length = 5 m
M′ — focal point = 5 m
Detector — focal point = 6.8 m
Detector — X-ray window = 1.7 m

Fig. 4. LCS experimental setup.
Production of high brightness $\gamma$ rays through backscattering of laser photons on high-energy electrons

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Based on the requirements from a conceptual design of a polarized positron beam for future linear colliders, we constructed a special collision system with a short focal length of 150 mm of the laser beams so as to produce $\gamma$ rays through inverse Compton scattering. In order to achieve efficient laser-electron collisions, we created a special optics to produce very small $e^-$-beam sizes of $\sigma_{e^+} = 7.6$ $\mu$m and $\sigma_{e^-} = 5.4$ $\mu$m in the horizontal and vertical directions at the collision point. Using laser light with a wavelength of 532 nm and an $e^-$ beam of 1.28 GeV, provided from the ATF-damping ring at KEK, we generated $2 \times 10^9$ $\gamma$ rays with a time duration of 26 ps in rms, leading to a peak brightness of $1.7 \times 10^{18} / (\text{rad}^2 \text{mm}^2 \text{ps})^{0.1 \% \text{bandwidth}}$ near to the maximum energy of 56 MeV.
FIG. 17. (Color) Number of detected γ rays; the white histogram shows the laser-off signal and the red one shows the laser-on signal.
Polarimetry of Short-Pulse Gamma Rays Produced through Inverse Compton Scattering of Circularly Polarized Laser Beams


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(Received 2 May 2003; published 17 October 2003)

We have developed a polarimetry of ultrashort pulse $\gamma$ rays based on the fact that $\gamma$ rays penetrating in the forward direction through a magnetized iron carry information on the helicity of the original $\gamma$ rays. Polarized, short-pulse $\gamma$ rays of $(1.1 \pm 0.2) \times 10^6$/bunch with a time duration of 31 ps and a maximum energy of 55.9 MeV were produced via Compton scattering of a circularly polarized laser beam of 532 nm off an electron beam of 1.28 GeV. The first demonstration of asymmetry measurements of short-pulse $\gamma$ rays was conducted using longitudinally magnetized iron of 15 cm length. It is found that the $\gamma$-ray intensity is in good agreement with the simulated value of $1.0 \times 10^6$. Varying the degree of laser polarization, the asymmetry for 100% laser polarization was derived to be $(1.29 \pm 0.12)\%$, which is also consistent with the expected value of $1.3\%$. 
### TABLE I. Parameters of the $e^-$ and laser beams. \( \sigma_{x,y} \), beam size at the collision point; \( \epsilon_{x,y} \), emittance; \( \beta_{x,y} \), beta function; \( \sigma_z / \beta_p \), momentum spread.

<table>
<thead>
<tr>
<th></th>
<th>Electron beam</th>
<th>Laser beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>1.28 GeV</td>
<td>2.33 eV (532 nm)</td>
</tr>
<tr>
<td>Intensity</td>
<td>( 0.65 \times 10^{10} ) ( \text{e}^- )/bunch</td>
<td>400 mJ/pulse</td>
</tr>
<tr>
<td>Bunch length (rms)</td>
<td>31 ps</td>
<td>3.6 ns</td>
</tr>
<tr>
<td>( \sigma_x )</td>
<td>87 ( \mu )m</td>
<td>154 ( \mu )m</td>
</tr>
<tr>
<td>( \sigma_y )</td>
<td>72 ( \mu )m</td>
<td>151 ( \mu )m</td>
</tr>
<tr>
<td>( \epsilon_x )</td>
<td>( 1.94 \times 10^{-9} ) rad m</td>
<td>( 11.5 \times 10^{-8} ) rad m</td>
</tr>
<tr>
<td>( \epsilon_y )</td>
<td>( 2.36 \times 10^{-11} ) rad m</td>
<td>( 12.9 \times 10^{-8} ) rad m</td>
</tr>
<tr>
<td>( \beta_x )</td>
<td>0.513 m</td>
<td>0.104 m</td>
</tr>
<tr>
<td>( \beta_y )</td>
<td>52.859 m</td>
<td>0.058 m</td>
</tr>
<tr>
<td>Rep. rate</td>
<td>3.12 Hz</td>
<td>1.56 Hz</td>
</tr>
<tr>
<td>( \sigma_z / \beta_p )</td>
<td>( 8.2 \times 10^{-4} )</td>
<td>...</td>
</tr>
</tbody>
</table>

**FIG. 4.** Efficiency of the air Cherenkov counter, defined as the number of Cherenkov photons arriving at the PMT per one incident \( \gamma \) photon.
THE HI\gamma S FACILITY: A FREE-ELECTRON LASER GENERATED GAMMA-RAY BEAM FOR RESEARCH IN NUCLEAR PHYSICS

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Fig. 11. Photon scattering spectra off a BaNO₃ sample observed at a polar angle $\theta = 90^\circ$ in the polarization plane of the incident $\gamma$-ray beam (top) and perpendicular to the polarization plane (bottom). The arrows mark known dipole excitations of $^{138}\text{Ba}$. 
Identification of the $J^\pi = 1^-$ two-phonon state of $^{88}\text{Sr}$

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(Received 18 January 2002; published 4 April 2002)

The linearly polarized $\gamma$-ray beam produced by the HIγS facility has been used to determine the parity of two previously known dipole excitations in $^{88}\text{Sr}$. The azimuthal asymmetry of $\gamma$ rays produced in the process of nuclear resonance fluorescence indicated that the dipole state at 4.742 MeV, recently discussed as a new form of $M1$ excitation, is in fact a $1^-$ ($E1$) state. The $1^-$ state at 4.742 MeV must, therefore, be reconsidered as the $J^\pi = 1^-$ member of the quadrupole-octupole coupled two-phonon multiplet. A second state at 7.535 MeV was also assigned $J^\pi = 1^-$. 

DOI: 10.1103/PhysRevC.65.047305 PACS number(s): 21.10.Hw, 25.20.Dc, 27.50.+e, 41.60.Cr
First measurement of the near-threshold $^2H(\gamma,n)p$ analyzing power using a free-electron laser based $\gamma$-ray source

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(Received 2 February 2000; published 18 May 2000)

The first measurement of the $^2H(\gamma,n)p$ analyzing power near threshold has been performed using the High-Intensity Gamma-ray Source (HIGS) at the Duke Free-Electron Laser Laboratory. A 3.58 MeV $\gamma$-ray beam having an energy resolution of 2.5% and 100% linear polarization was incident on an active $^2H_2$ target. Outgoing neutrons were detected parallel and perpendicular to the plane of $\gamma$-ray polarization at a lab angle of 150°. The experimentally determined analyzing power provides a sensitive measurement of the relative $E1$ and $M1$ contributions to the total cross section.

PACS number(s): 25.20.-x, 24.70.+s, 27.10.+h, 21.45.+v
Parity Measurements of Nuclear Levels Using a Free-Electron-Laser Generated $\gamma$-Ray Beam

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(Received 18 July 2001; published 20 December 2001)

The quality and intensity of $\gamma$ rays at the High Intensity $\gamma$-ray Source are shown to make nuclear resonance fluorescence studies possible at a new level of precision and efficiency. First experiments have been carried out using an intense ($10^7 \gamma$/s) beam of 100% linearly polarized, nearly monoenergetic, $\gamma$ rays on the semimagic nucleus $^{138}$Ba. Negative parity quantum numbers have been assigned to 18 dipole excitations of $^{138}$Ba between 5.5 MeV and 6.5 MeV from azimuthal $\gamma$-intensity asymmetries.

DOI: 10.1103/PhysRevLett.88.012502 PACS numbers: 21.10.Hw, 25.20.Dc, 27.60.+j, 41.60.Cr
FIG. 1. Photon scattering spectra obtained using a BaNO$_3$ target with detectors at $\theta = 90^\circ$ (a) in the polarization plane of the incident $\gamma$ beam, and (b) perpendicular to that plane. The arrows mark the known [23] dipole excitations of $^{138}$Ba. The dashed curve in (a) is a Gaussian with FWHM = 185(8) keV obtained from an error-weighted least-squares fit to the seven data points for the $\gamma$-beam intensity, plotted in arbitrary units.
Experimental characterization of an ultrafast Thomson scattering x-ray source with three-dimensional time and frequency-domain analysis


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(Received 30 January 2004; published 11 June 2004)

We present a detailed comparison of the measured characteristics of Thomson backscattered x rays produced at the Picosecond Laser-Electron Interaction for the Dynamic Evaluation of Structures facility at Lawrence Livermore National Laboratory to predicted results from a newly developed, fully three-dimensional time and frequency-domain code. Based on the relativistic differential cross section, this code has the capability to calculate time and space dependent spectra of the x-ray photons produced from linear Thomson scattering for both bandwidth-limited and chirped incident laser pulses. Spectral broadening of the scattered x-ray pulse resulting from the incident laser bandwidth, perpendicular wave vector components in the laser focus, and the transverse and longitudinal phase spaces of the electron beam are included. Electron beam energy, energy spread, and transverse phase space measurements of the electron beam at the interaction point are presented, and the corresponding predicted x-ray characteristics are determined. In addition, time-integrated measurements of the x rays produced from the interaction are presented and shown to agree well with the simulations.
PLEIADES: A picosecond Compton scattering x-ray source for advanced backlighting and time-resolved material studies\textsuperscript{a)}

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The PLEIADES (Picosecond Laser-Electron Inter-Action for the Dynamical Evaluation of Structures) facility has produced first light at 70 keV. This milestone offers a new opportunity to develop laser-driven, compact, tunable x-ray sources for critical applications such as diagnostics for the National Ignition Facility and time-resolved material studies. The electron beam was focused to 50 μm rms, at 57 MeV, with 260 pC of charge, a relative energy spread of 0.2%, and a normalized emittance of 5 mm mrad horizontally and 13 mm mrad vertically. The scattered 820 nm laser pulse had an energy of 180 mJ and a duration of 54 fs. Initial x rays were captured with a cooled charge-coupled device using a cesium iodide scintillator; the peak photon energy was approximately 78 keV, with a total x-ray flux of $1.3 \times 10^6$ photons/shot, and the observed angular distribution found to agree very well with three-dimensional codes. Simple K-edge radiography of a tantalum foil showed good agreement with the theoretical divergence-angle dependence of the x-ray energy. Optimization of the x-ray dose is currently under way, with the goal of reaching $10^8$ photons/shot and a peak brightness approaching $10^{20}$ photons/mm$^2$/mrad$^2$/s/0.1% bandwidth.

© 2004 American Institute of Physics. [DOI: 10.1063/1.1646160]
FIG. 3. Diagram of the PLEIADES interaction region, showing the laser, electron, and x-ray beam paths. The x rays, produced in the scattering of the laser off the electron beam, pass through the laser mirror as they exit the interaction region.

FIG. 6. (Color) X-ray profile after transmission through 0.005 in. tantalum foil. (a) Predicted profile with 55 MeV e-beam energy. (b) Predicted profile with 57 MeV e-beam energy. (c) Measured profile with 55 MeV e-beam energy. (d) Measured profile with 57 MeV e-beam energy.
Characterization of a bright, tunable, ultrafast Compton scattering X-ray source

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(RECEIVED 1 November 2003; ACCEPTED 26 January 2004)
Fig. 12. Top: False color image of the X-ray angular energy distribution captured by the CCD over 10 s of integration. Bottom: Lorentzian distribution $(1 + \gamma^2 \theta^2)^{-1}$ along the direction of polarization, for $\gamma = 107$ (red); experimental data (blue dots); and theoretically calculated pattern after transmission through the BK7 mirror, taking into account the energy-dependent response of the CCD (green).
Experiment on gamma-ray generation and application

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Abstract

An experimental setup of gamma-ray generation through laser Compton scattering has been built on the NewSUBARU storage ring. The aim is to study nuclear transmutation, which is regarded as the first stage to explore the feasibility of developing a nuclear waste disposal system based on the concept of irradiating long-lived fission products by laser Compton scattering gamma ray. In this paper, the gamma-ray generation facility is presented, and some experimental results such as gamma-ray energy spectrum, intensity distribution, and the coupling efficiency of nuclear transmutation, are given. The experimental data is in good agreement with the analytic calculation or simulation analysis.

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Fig. 3. Gamma-ray energy spectrum detected by Ge detector.

Fig. 5. Image of gamma-ray indicates its spatial distribution of intensity.
Thomson-Backscattered X Rays From Laser-Accelerated Electrons

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(Received 6 September 2005; published 10 January 2006)

We present the first observation of Thomson-backscattered light from laser-accelerated electrons. In a compact, all-optical setup, the “photon collider,” a high-intensity laser pulse is focused into a pulsed He gas jet and accelerates electrons to relativistic energies. A counterpropagating laser probe pulse is scattered from these high-energy electrons, and the backscattered x-ray photons are spectrally analyzed. This experiment demonstrates a novel source of directed ultrashort x-ray pulses and additionally allows for time-resolved spectroscopy of the laser acceleration of electrons.
Efficient Propagation of Polarization from Laser Photons to Positrons through Compton Scattering and Electron-positron Pair Creation


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We have demonstrated for the first time the production of highly polarized short-pulse positrons with a finite energy spread in accordance with a new scheme that consists of two-quantum processes, such as inverse Compton scattering and electron-positron pair creation. Using a circularly polarized laser beam of 532 nm scattered off a high-quality, 1.28 GeV electron beam, we have obtained polarized positrons with an intensity of $2 \times 10^4$ e$^+$/bunch. The magnitude of positron polarization has been determined to be $73 \pm 15$ (stat) $\pm 19$ (syst)% by means of a newly designed positron polarimeter.

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FIG. 2. (a) Differential cross section of the Compton scattering for right-handed polarized laser photons with wavelength of 532 nm backscattered off 1.28 GeV electrons as a function of the γ-ray energy. The dashed and dotted curves correspond to the helicities of +1 and −1 for the γ rays, respectively. (b) Differential cross section of the positron creation (electron-positron pair creation) in the thin tungsten target calculated using the γ-ray distribution given in Fig. 2(a). The dashed and dotted curves correspond to the helicities of +1 and −1 for the positrons.

FIG. 3 (color). Experimental setup of the polarized γ-ray production system including the Compton chamber with three cells, the laser optics with three remotely controllable mirrors, and electron beam line. Laser-electron collisions take place at the central cell of the Compton chamber.
Determination of electron beam parameters by means of laser-Compton scattering

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Laser-Compton scattering (LCS) experiments were carried out at the Idaho Accelerator Center using the 5 ns (FWHM) and 22 MeV electron beam. The electron beam was brought to an approximate head-on collision with a 29 MW, 7 ns (FWHM), 10 Hz Nd:YAG laser. Clear and narrow x-ray peaks resulting from the interaction of relativistic electrons with the Nd:YAG laser second harmonic line at 532 nm were observed. We have developed a relatively new method of using LCS as a nonintercepting electron beam monitor. Our method focused on the variation of the shape of the LCS spectrum rather than the LCS intensity as a function of the observation angle in order to extract the electron beam parameters at the interaction region. The electron beam parameters were determined by making simultaneous fits to spectra taken across the LCS x-ray cone. This scan method allowed us also to determine the variation of LCS x-ray peak energies and spectral widths as a function of the detector angles. Experimental data show that in addition to being viewed as a potential bright, tunable, and quasimonochromatic x-ray source, LCS can provide important information on the electron beam pulse length, direction, energy, angular and energy spread. Since the quality of LCS x-ray peaks, such as degree of monochromaticity, peak energy and flux, depends strongly on the electron beam parameters, LCS can therefore be viewed as an important nondestructive tool for electron beam diagnostics.
\( E_\gamma = 18.09 \pm 0.01 \text{ keV} \)
\( \Delta E_\gamma = 0.73 \pm 0.02 \text{ keV} \)
SM = 150
Sub-MeV tunably polarized X-ray production with laser Thomson backscattering


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Reported in this article is the generation of unique polarized x-rays in the sub-MeV region by means of the Thomson backscattering of the Nd:YAG laser photon with a wavelength of 1064 nm on the 150 MeV electron from the microtron accelerator. The maximum energy of the x-ray photons is estimated to be about 400 keV. The total energy of the backscattered x-ray pulse is measured with an imaging plate and a LYSO scintillator. The angular divergence of the x-rays is also measured by using the imaging plate. We confirm that the x-ray beam is polarized according to the laser polarization direction with the Compton scattering method. In addition, we demonstrate the imaging of the object shielded by lead with the generated x-rays. © 2008 American Institute of Physics.

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TABLE 1. Summary of the electron beam and Nd:YAG laser parameters on the experiment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electron beam</strong></td>
<td></td>
</tr>
<tr>
<td>Beam energy</td>
<td>150 MeV</td>
</tr>
<tr>
<td>Beam charge</td>
<td>60 pC/pulse</td>
</tr>
<tr>
<td>Horizontal</td>
<td>35π mm mrad</td>
</tr>
<tr>
<td>Vertical</td>
<td>8π mm mrad</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>10 ps (rms)</td>
</tr>
<tr>
<td>Repetition</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Spot size (standard deviation)</td>
<td></td>
</tr>
<tr>
<td>Horizontal (σ_{x1})</td>
<td>(9.7 ± 0.9) × 10^{-3} cm</td>
</tr>
<tr>
<td>Vertical (σ_{y1})</td>
<td>(7.2 ± 0.1) × 10^{-3} cm</td>
</tr>
<tr>
<td><strong>Spatial jitter</strong></td>
<td></td>
</tr>
<tr>
<td>Horizontal (σ_{x_j})</td>
<td>1.2 × 10^{-3} cm</td>
</tr>
<tr>
<td>Vertical (σ_{y_j})</td>
<td>3.2 × 10^{-3} cm</td>
</tr>
<tr>
<td><strong>Nd:YAG laser</strong></td>
<td></td>
</tr>
<tr>
<td>Wavelength</td>
<td>1064 nm (fundamental light)</td>
</tr>
<tr>
<td>Energy at focal point</td>
<td>0.84 J/pulse</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>23 ns (FWHM)</td>
</tr>
<tr>
<td>Repetition</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Polarization</td>
<td>linear (on horizontal plane)</td>
</tr>
<tr>
<td>Spot size (standard deviation)</td>
<td></td>
</tr>
<tr>
<td>Horizontal (σ_{h})</td>
<td>2.7 × 10^{-3} cm</td>
</tr>
<tr>
<td>Vertical (σ_{v})</td>
<td>2.2 × 10^{-3} cm</td>
</tr>
</tbody>
</table>

*Reference 37.*

FIG. 7. The angular divergence of the generated x-rays is observed by using imaging plates. (a) the laser-on case and (b) the laser-off case. [(c) and (d)] The projections of each image to the horizontal axis. A lead sheet with a thickness of 5 mm is installed in front of the imaging plate for the background reduction. The exposure time is 1 h for each case, respectively. We find that there is a clear difference at the central part of these images by comparing [(a) and (c)] the laser-on case with [(b) and (d)] the laser-off case. The spread of this excess at the central part corresponds to the divergence angle of 3 mrad from the x-ray source point.
Energy and energy spread measurements of an electron beam by Compton scattering method

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A gamma-ray beam produced by Compton scattering of a laser beam with an electron beam can be used to measure the electron beam parameters. In several published works, a simple fitting model has been applied to determine the electron beam energy and energy spread without considering the gamma beam collimation and electron beam emittance effects. This fitting model is rederived in this work, and the underlying assumptions and resultant limitations are discussed. To overcome these limitations, a new fitting model is proposed, which takes into account the collimation and emittance effects. Using the new model and a gamma-ray beam produced at the high intensity γ-ray sources facility at Duke University, we have successfully determined the electron beam energy with a relative uncertainty of about $3 \times 10^{-5}$ around 460 MeV as well as the electron beam energy spread. We also experimentally demonstrated for the first time that a small relative energy change (about $4 \times 10^{-5}$) of the electron beam by varying the storage ring dipole field can be directly detected using the Compton scattering technique.
FIG. 7. (Color) Schematic of the HIY S beam production and measurement at Duke University.

FIG. 8. (Color) A typical HIY S beam spectrum measured by a large volume 123\% efficiency HPGe detector. The radiation sources of $^{226}$Ra and $^{60}$Co as well as the nature background from $^{40}$K are used in the real time for the detector energy calibration.

FIG. 11. (Color) An illustration of the fitting on the high energy edge of the measured gamma beam spectrum. The least squares method is used to fit Eq. (16). The goodness of fit is given by the reduced $\chi^2$. The fit electron beam energy $E_e$ and relative energy spread $\sigma_{E}/E_e$ as well as the fitting errors associated with them are also shown in the plot.
A laser-Compton scattering prototype experiment at 100 MeV linac of Shanghai Institute of Applied Physics

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As a prototype of the Shanghai Laser Electron Gamma Source in the Shanghai Synchrotron Radiation Facility, an x-ray source based on laser-Compton scattering (LCS) has been installed at the terminal of the 100 MeV linac of the Shanghai Institute of Applied Physics. LCS x-rays are generated by interactions between Q-switched Nd:yttrium aluminum garnet laser pulses [with wavelength of 1064 nm and pulse width of 21 ns (full width at half maximum)] and electron bunches [with energy of 108 MeV and pulse width of 0.95 ns (rms)] at an angle of 42° between laser and electron beam. In order to measure the energy spectrum of LCS x-rays, a Si(Li) detector along the electron beam line axis is positioned at 9.8 m away from a LCS chamber. After background subtraction, the LCS x-ray spectrum with the peak energy of 29.1 ± 4.4_{stat} ± 2.1_{syst} keV and the peak width (rms) of 7.8 ± 2.8_{stat} ± 0.4_{syst} keV is observed. Normally the 100 MeV linac operates with the electron macropulse charge of 1.0 nC/pulse, and the electron and laser collision repetition rate of 20 Hz. Therefore, the total LCS x-ray flux of (5.2 ± 2.0) × 10^2 Hz can be achieved. © 2010
FIG. 2. (Color online) LCS experimental setup.
Isotope-specific detection of low-density materials with laser-based monoenergetic gamma-rays


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What we believe to be the first demonstration of isotope-specific detection of a low-Z and low density object shielded by a high-Z and high-density material using monoenergetic gamma rays is reported. The isotope-specific detection of LiH shielded by Pb and Al is accomplished using the nuclear resonance fluorescence line of $^7$Li at 478 keV. Resonant photons are produced via laser-based Compton scattering. The detection techniques are general, and the confidence level obtained is shown to be superior to that yielded by conventional x-ray and γ-ray techniques in these situations. © 2010 Optical Society of America

OCIS codes: 340.7480, 000.2190.
Fig. 1. T-REX experimental layout and detection with HPGe detectors.

Fig. 2. (Color online) Experimentally measured on-axis spectra (dots) and corresponding Monte Carlo simulation (dashed).