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## MeV-Energy X Rays from Inverse Compton Scattering with Laser-Wakefield Accelerated Electrons

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Phys. Rev. Lett. **110**, 155003 — Published 10 April 2013

DOI: [10.1103/PhysRevLett.110.155003](https://doi.org/10.1103/PhysRevLett.110.155003)

## **Titles**

MeV-energy x-rays from all-laser-driven electron acceleration and synchrotron radiation

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## Abstract

We report the generation of MeV x-rays using an undulator and accelerator that are both driven by the same 100-terawatt laser system. The laser pulse driving the accelerator and the scattering laser pulse are independently optimized to generate high energy electron beam ( $> 200$  MeV) and maximize the output x-ray brightness. The total x-ray photon number was measured to be  $2 \times 10^7$ , the source size was  $5 \mu\text{m}$ , and the beam divergence angle was  $\sim 10$  mrad. The x-ray photon energy, peaked at 1 MeV (reaching up to 4 MeV), exceeds the thresholds of fundamental nuclear processes (*e.g.*, pair production and photodisintegration).

By generating x-rays with photon energy reaching the MeV level, inverse-Compton-scattering sources (also referred to as Thomson sources) have enabled the use of synchrotron light for nuclear physics research, as well as for numerous novel radiological applications [1-3]. Compton sources are usually quite large ( $> 100$  m) though when they rely on large conventional electron accelerators. They can however be substantially smaller—and yet generate bright x-rays—when driven instead by a compact advanced laser-wakefield electron accelerator (LWFA), which can accelerate electrons to GeV energy in a distance of only a few centimeters [4-6].

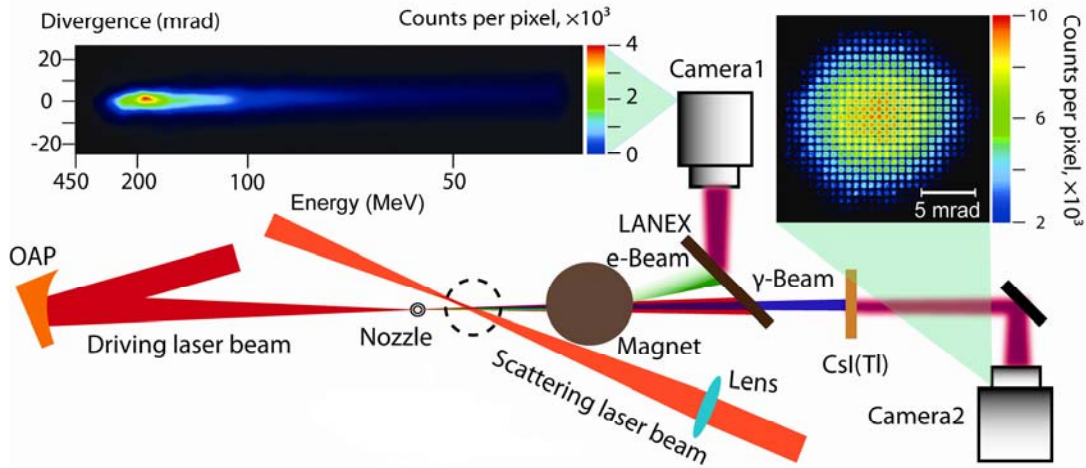
In a previous study of a LWFA-based Compton source, only soft x-rays ( $\sim 1$ -keV) without beam properties are reported [7]. More recently, a single laser pulse is used to both accelerate the electrons and scatter (after reflection from a plasma mirror) [8]. While hard x-rays are produced in this latter case (peaked at  $\sim 50$ -keV), the photon energy is still well below the thresholds for photonuclear processes.

We report here an all-optically-driven Compton scattering source of gamma-ray ( $\gamma$ -ray) energy x-rays. The x-ray output parameters could be optimized by employing two independent laser pulses from the same high-peak-power laser system—one pulse optimized for accelerating electrons by a laser wakefield, and the other pulse optimized for Compton scattering. The electron beam and scattering pulse were spatially overlapped (and temporally synchronized) with micron (femtosecond) accuracy. Besides optimization of the x-ray output, the ability to independently adjust the parameters of the two laser pulses has several other advantages. It permits scalability to higher  $\gamma$ -ray flux

with increasing scattering laser pulse energy. A cross-correlation technique was used to characterize the source sizes of both the electron beam and  $\gamma$ -ray beam, by scanning the scattering laser pulse across the electron beam. This design is also free from the debris contamination and bremsstrahlung background, both of which are inherent to the single-laser-pulse approach [8]. Characterization of higher energy x-rays required both the development of a novel detection method, as well as implementation of a novel numerical scattering model.

The experiments were conducted using the 100-TW Diocles laser at the University of Nebraska, Lincoln, which operates with a 10-Hz repetition rate, and at a central wavelength of 800 nm [9]. The accelerator drive pulse and scattering pulse were both generated from the same laser pulse by means of an optical beamsplitter with 80/20 percent split ratio. A deformable mirror corrected the wavefront and improved the focal quality of both beams. Figure 1 shows the schematic of the setup. The 1.9-J, 35-fs drive laser pulse was focused by a 1-m focal length parabolic reflector onto a 2 mm supersonic gas target (mixture of 99% helium and 1% nitrogen) with a Gaussian full-width half maximum (FWHM) focal spot size of 20  $\mu\text{m}$ . 33% of the laser energy of the driven pulse was enclosed in the FWHM width, and it corresponded to a peak intensity of  $7.4 \times 10^{18}$  W/cm<sup>2</sup> (normalized vector potential of  $a_0 = 1.9$ ). The plasma density of the target was  $1.0 \times 10^{19}$ /cm<sup>3</sup>. As such, the LWFA was operated in the ionization-injected, self-guided, and bubble regime [10,11]. The energy and the charge of generated electron beam (e-beam) were monitored by a magnetic spectrometer, consisting of a calibrated LANEX screen and imaged by a 12-bit CCD camera, on every shot. The magnetic spectrometer

has an energy cut-off around 50 MeV due to the size of the LANEX screen. The electron beam is optimized in the experiment, in terms of energy and charge, by controlling both the plasma density and the focal position of the driving laser beam (relative to the gas target). With these optimizations, electron beams were produced with cut-off energy  $\sim 250$  MeV, and total integrated charge of  $\sim 0.1$  nC (for energies  $> 50$  MeV). The 0.5-J, 90-fs scattering laser beam was focused by a 1-m focal length lens. To take into account the effect of the B integral of the focusing lens and beamsplitter on the focus spot quality at high laser power, the scattering laser beam focal spot was measured with the same laser power used in the experiment. The measured focal spot was 22  $\mu\text{m}$  FWHM (RMS spot size  $\sigma_L = 9 \mu\text{m}$ ) with 16% of its energy enclosed in the FWHM width as shown in Figure 2, corresponding to a peak focused intensity of  $3.4 \times 10^{17} \text{ W/cm}^2$  ( $a_0 = 0.4$ ). Figure 2 shows the overlapping geometry, in which the scattering laser beam counter-propagates at an angle of  $\Phi=170^\circ$  (in the horizontal plane) to the e-beam. The interaction point was located in the vacuum region 1-mm downstream from the exit of the laser plasma accelerator [12].



**Fig. 1: All-laser-driven Compton  $\gamma$  ray source.** Schematic of the experimental setup. Left inset shows the electron energy spectrum as recorded by LANEX screen, which was imaged by CCD camera. Right inset shows the  $\gamma$ -ray beam profile measured by pixelated CsI(Tl) scintillator imaged by EMCCD camera.

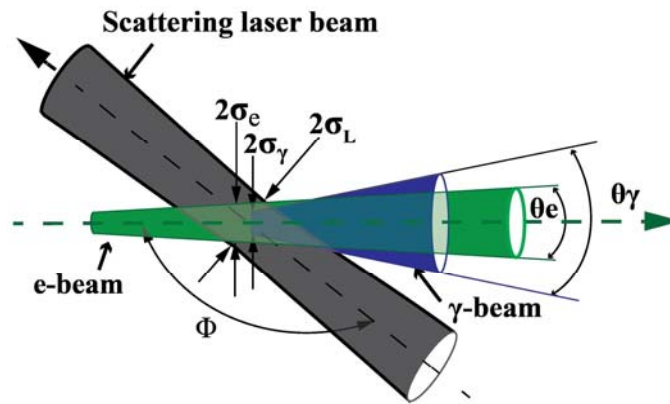
From the energy scaling formula of Compton scattering  $E_{\gamma} = 4\gamma^2 E_L$ , where  $E_{\gamma}$  is the gamma ray photon energy,  $\gamma$  is the electron relativistic factor and  $E_L$  is the laser photon energy, we expect to generate 1.4 MeV gamma ray by scattering 1.5 eV photons off 250 MeV electron beam. To detect and characterize the high energy x-ray beam generated in this experiment with optimal response and high spatial resolution, we used a CsI-crystal scintillator, which consisted of a 1-cm deep,  $40 \times 40$  array of  $1.0 \times 1.0 \times 10$ -mm “voxels” (3D pixels), with a 0.2-mm epoxy layer between voxels (Dynasil Corporation, Massachusetts, USA ).

The CsI(Tl) scintillator was placed on-axis ( $\Phi=180^\circ$ ) at a distance of 1.72 m from the interaction point. The optical light signal from the CsI(Tl) detector was imaged onto a 14-bit EMCCD camera. This  $\gamma$ -ray detection system was calibrated using a Cs<sup>137</sup> radiation source of known activity. A lead baffle was placed in front of the scintillator to shield the detector from background noise, and the detection system had a signal to noise ratio of 20:1. Figure 1 (right inset) shows a typical background-subtracted single-shot image of the  $\gamma$ -ray beam with the corresponding e-beam spectrum shown in Figure 1 (left inset). The  $\gamma$ -ray beam typically had a  $\sim 10$ -mrad divergence angle, a near-circular shape, and a Gaussian profile. With a consecutive run of 50 laser shots  $\gamma$ -ray beams were observed in 90% percent of these shots. The fluctuation was mainly due to the electron beam pointing fluctuation, which can be determined from the electron beam angular position on the LANEX screen. No  $\gamma$ -rays were observed in any of the  $\sim 400$  laser shots for which the scattering beam was blocked.

Several theoretical predictions have been made for the performance of Compton sources when LWFA e-beams are used [13]. We developed our own benchmarked numerical code to calculate the angle-resolved  $\gamma$ -ray spectrum [14], using the experimentally measured characteristics of the scattering laser beam and e-beam (see Table 1) as input. The simulated  $\gamma$ -ray parameters were then used as the input for a Monte-Carlo simulation (MCNPX code) in order to produce a simulated  $\gamma$ -ray beam profile image [15], which could be compared to the measured one, shown in Figure 1 (right inset). With the input electron beam six dimension phase space parameters reconstructed from the energy spectrum and divergence angle shown in Figure 1 (left inset), the simulated  $\gamma$ -ray beam



profile had a divergence of 11.3 mrad, which had a good agreement with the experimentally measured value, 12.7 mrad. The simulation also predicted a total photon number of  $2 \times 10^7$ , which had reasonable agreement with the experimentally measured photon number of  $\sim 1 \times 10^7$ .

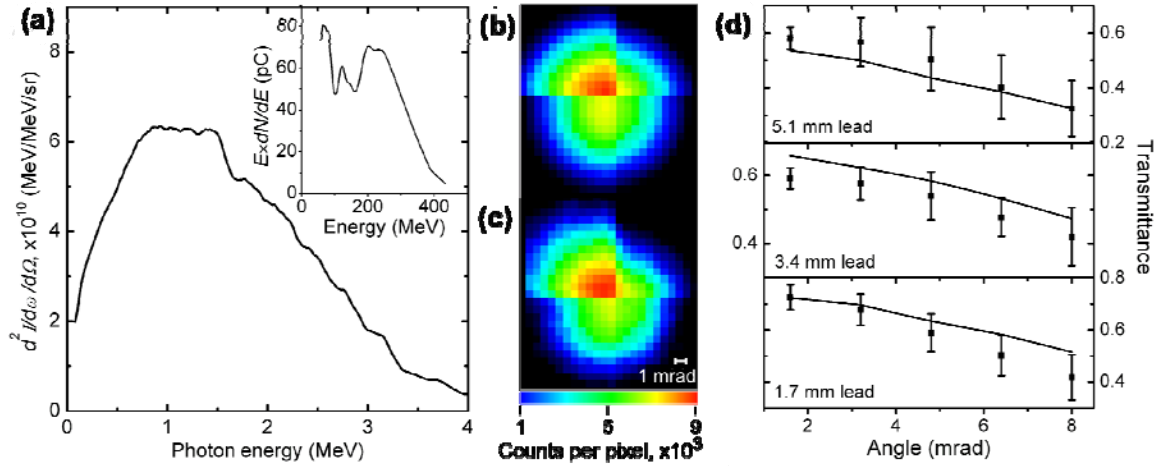


**Fig. 2: Interaction geometry defining beam parameters.**

To reveal the gamma ray spectrum, a quadrant filter (crossed plates of 1.7 mm lead and 3.4 mm lead) is placed in front of the CsI detector. The measured quad-filtered image is shown in Figure 3c. The transmittance of different thickness filters at different divergence angles is shown in Figure 3d. The transmittance measurement not only showed the x-ray source has high photon energy because of the penetration of 5.1 mm lead, but also revealed angular dependence of the x-ray source spectrum, since transmittance is lower at large divergence angle for each quadrant.

Based on the measured e-beam energy spectrum, shown in Figure 3a (inset), a simulated on-axis  $\gamma$ -ray intensity spectrum is obtained, as shown in Figure 3a, which is peaked at

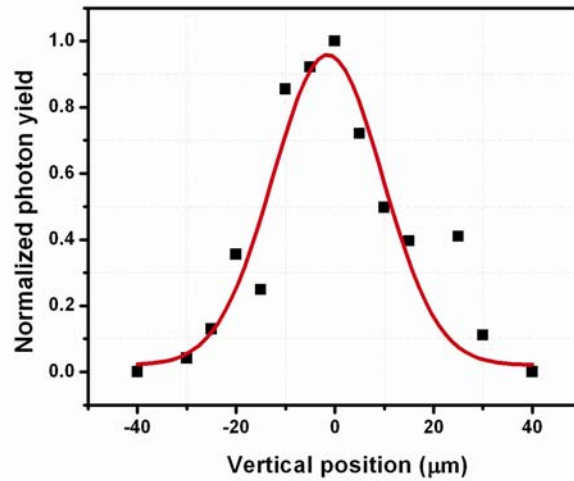
1 MeV and extends to 4 MeV. Simulated x-ray spectra for each angle were used to create a simulated image of filtered  $\gamma$ -ray beam profile. Comparisons of the simulated and measured x-ray transmission levels through the various filter thicknesses and at various polar angles are shown in Figure 3d. (The error bars in Figure 3d originate from uncertainties in the background subtraction levels, and the beam-center location on the CsI.) The analysis shows that the simulated and measured transmittances agree within the experimental uncertainty, and thus the simulated spectrum can be used to represent the experimental spectrum. To show the peak-energy sensitivity of our quad filter-based measurement, we shifted the simulated x-ray spectrum with 0.1 MeV steps from -0.6 to +0.6 MeV, and reconstructed CsI images for each step (See Supplemental Material at *[URL will be inserted by publisher]* for sensitivity of quadrant filter measurement relative to spectra peak shift). To estimate the similarity between these images and an experimentally measured one, we took the difference of the images (normalized-measured minus normalized-simulated) and calculated the mean and standard deviation (SD) for each image. Both figures-of-merits are close to their minima for unshifted spectrum, demonstrating that the quadrant filters method has a peak sensitivity of at least  $\pm 0.2$  MeV.



**Fig. 3:  $\gamma$ -ray spectrum.** (a) Simulated on-axis  $\gamma$ -ray spectrum, with corresponding e-beam spectrum (inset). (b) Simulated  $\gamma$ -ray beam profile transmitted through quad filter (not attenuated at top-left corner, 1.7 mm lead at top-right, 3.4 mm lead at bottom-left, 5.1 mm lead at bottom-right). (c) Measured  $\gamma$ -ray beam profile transmitted through quad filter. (d) Comparison between simulated and measured  $\gamma$ -ray transmittances through different filters, as a function of divergence angle. The solid line represents the simulated transmittance and square dots represent the measured transmittance.

Another important parameter of the  $\gamma$ -ray source is the source size. Methods based on diffraction, that are usually used to measure the source size of keV x-rays [8,16,17], cannot be applied to the  $\gamma$ -ray source due to the high photon energy ( $\sim$ MeV). Instead, we exploit the spatial cross-correlation technique to measure the radiation source size [18--21], in which the scattering beam focal spot was scanned vertically across the e-beam over a spatial range of 90  $\mu$ m. The shots with similar electron beam pointing and spectra were first selected from each scanning position. The recorded  $\gamma$ -ray beam profiles were

then analyzed, and the resulting photon yield, as a function of radius, is shown in Figure 4. A Gaussian spatial profile is assumed for both the laser and e-beam, with the width of the cross-correlation profile given by  $\sigma_{\text{signal}} = (\sigma_L^2 + \sigma_e^2)^{1/2}$ , where  $\sigma_e$  and  $\sigma_L$  are the RMS widths of electron beam and laser beam, respectively, at the interaction point. A Gaussian profile was fitted to the data points and the best fit was obtained with  $\sigma_{\text{signal}} = 11 \mu\text{m}$  with a fitting error of  $\pm 1 \mu\text{m}$ . With the measured focal spot size of the laser pulse,  $\sigma_L = 9$  with a measurement error of  $\pm 1 \mu\text{m}$ , and width of the cross-correlation trace, the e-beam size was estimated, by deconvolution of the cross-correlation curve, to be  $\sigma_e = 6 \pm 3 \mu\text{m}$ . The  $\gamma$ -ray source size  $\sigma_\gamma$  is given by the products of electron and laser beam distribution  $\sigma_\gamma = \sigma_L \sigma_e / (\sigma_L^2 + \sigma_e^2)^{1/2}$ , and  $\sigma_\gamma = 5 \pm 3 \mu\text{m}$ . The error in the source-size measurement is mainly attributed to uncertainty of the electron and laser beam positions relative to each other ( $\sigma_{\text{uncertainty}} = \pm 4 \mu\text{m}$ ).



**Fig. 4:  $\gamma$ -ray and electron radiation source size measurements.** Normalized  $\gamma$ -ray yield as a function of the laser pulse vertical position. Each data point represents the  $\gamma$ -ray yield obtained by integrating over a single-shot background-subtracted  $\gamma$ -ray beam profile image. The solid line is a Gaussian fit with an RMS width of  $11 \pm 1 \mu\text{m}$ . By deconvolving the cross-correlation trace, we estimate the RMS width of the e-beam size at the interaction point to be  $6 \pm 3 \mu\text{m}$ .

The peak on-axis x-ray brightness is estimated to be of the order of  $1 \times 10^{19}$  photons  $\text{s}^{-1}$ - $\text{mm}^{-2}$ - $\text{mrad}^{-2}$  (per 0.1% BW) at photon energies ranging from 0.9 MeV to 1.4 MeV. This estimate is based on our  $\gamma$ -ray results, reported above, and e-beam pulse duration of 35 fs (from previous relevant LWFA measurements [22,23]). The energy conversion efficiency from scattering laser pulse to gamma ray beam is in the order of  $\sim 10^{-6}$ .

The e-beam and scattering beam parameters are nearly optimal for Compton efficiency. The scattering beam was focused to as high an intensity as possible ( $a=0.4$ ) to maximize

the undulator strength, but not too high to generate nonlinear effects [24,25]. Its focal spot size (9  $\mu\text{m}$ ) was also chosen to closely match the size of the e-beam (6  $\mu\text{m}$ ) at the interaction point. This helps to increase the Compton scattering efficiency as the yield of Compton photon is inversely proportional to overlapping area. Additionally, both pulses—by virtue of being driven by the same laser system— were synchronized in time to each other, which eliminated timing jitter and allowed ultra-short duration pulses to be used without large fluctuations in their temporal overlap, and consequently the  $\gamma$ -ray output.

Besides providing a measurement of our  $\gamma$ -ray radiation source size, our Compton cross-correlation method also provided information on the LWFA e-beam. The source size of the e-beam (2  $\mu\text{m}$  (RMS)) was extrapolated from both the e-beam size measured at the Compton interaction point (6  $\mu\text{m}$  (RMS)) and its average divergence angle (10 mrad), assuming space-charge blow-up is negligible for our e-beam charge density and average energy [26]. Using the inferred source size, and the measured divergence angle of 5 mrad (for the 250-MeV component of the e-beam), we estimate a normalized RMS e-beam emittance ( $\epsilon_N = \sigma_{\text{e-source}} \mathcal{A}_{250\text{MeV}}$ ) of 1 mm-mrad at 250 MeV. This technique provides another method to characterize the emittance of LWFA electron beam, adding to the pepperpot and betatron radiation techniques that have already been reported [27--30].

In conclusion, gamma rays generated by all-optical-driven electron acceleration and Compton scattering were found to have total photon number of  $2 \times 10^7$ , divergence of  $\sim 10$  mrad, radiation source size of 5  $\mu\text{m}$ , and peak brightness of  $10^{19}$  photons  $\text{s}^{-1}\text{-mm}^{-2}\text{-mrad}^{-2}$

(per 0.1% BW). The gamma ray generation combined with a cross-correlation technique helped to characterize the properties of the electron beam generated from the LWFA. The current source has an on-axis *intensity* spectrum that peaks at photon energy of 1 MeV, even though the *photon-number* spectrum (without weighting by the photon energy) does not appear peaked. In future experiments, even the photon-number x-ray spectrum would be peaked if the more mono-energetic electron beams that have recently been demonstrated [31-34] were to be used. Wide tunability range and micron radiation source size would also be achieved, which could help to improve radiography and radiotherapy [35-37]. For example, with the current setup, a 200-MeV electron beam with a 6% energy spread (FWHM) will generate a 0.8-MeV energy gamma-ray beam with 24% energy spread (FWHM), when integrated over a  $1/\gamma$  radiation cone angle. MeV photon energy, combined with ultrashort pulse duration (fs), may also enable exploration of a new research direction; namely, ultrafast nuclear science [38,39].

We thank V. Ramanathan, N. Chandler-Smith, K. Brown, and J. Mills for their contributions to the laser facility. This material is based upon work supported by the U.S. Department of Energy: DE-FG02-05ER15663, Defense Threat Reduction Agency: HDTRA1-11-C-0001, Air Force Office for Scientific Research: FA 9550-08-1-0232, and FA9550-11-1-0157, Department of Homeland Security: 2007-DN-007-ER0007-02, and Defense Advanced Research Projects Agency: FA9550-09-1-0009.

Beam	Parameter	Symbol	Value
$\omega_0$	Energy	$E_{\text{laser}}$	0.5 J/ pulse
	Wavelength	$\lambda$	800 nm
	Pulse duration	$\tau_s$	90 fs (FWHM)
	Spotsize	$\sigma_L$	$9 \pm 1 \mu\text{m}$ (RMS)
	Number of laser oscillations/pulse	$N_{\text{laser}}$	34
	Average power	$P_L$	5.6 TW
	Normalized field strength	$a_0$	0.4
	Photon energy	$E_L$	1.5 eV
	Interaction angle	$\Phi$	170 deg
$e$	Source size	$\sigma_e$	$6 \pm 3 \mu\text{m}$ (RMS)
	Cutoff energy <sup>1</sup>	$E_c$	250 MeV
	Divergence <sup>2</sup>	$\theta_e$	5 mrad (FWHM)
	Total charge	$Q$	120 pC
$\gamma$	Source size	$\sigma_\gamma$	$5 \pm 3 \mu\text{m}$ (RMS)
	Divergence	$\theta_\gamma$	12.7 mrad (FWHM)
	Peak energy	$E_\gamma$	1.2 MeV
	Photons/pulse	$N_\gamma$	$\sim 10^7$
	Peak on-axis brilliance	$B_x$	$\sim 1 \times 10^{19}$ photons $\text{s}^{-1}\text{-mm}^{-2}\text{-mrad}^{-2}$ (per 0.1% BW)

**Table 1:** Typical experimental parameters for scattering laser ( $\omega_0$ ), electron ( $e$ ), and gamma ( $\gamma$ ) beams.

<sup>1</sup> Corresponds to energy at 10% of the peak value of the electron spectrum.

<sup>2</sup> Corresponds to the divergence of the beam at the cutoff energy.



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