Bright 5-85 MeV Compton γ-ray pulses from GeV laser-plasma electron accelerator and plasma mirror

J. M. Shaw, A. C. Bernstein, R. Zgadzaj, A. Hannasch, M. LaBerge, Y. Y. Chang, K. Weichman, J. Welch, W. Henderson, H.-E. Tsai, N. Fazel, X. Wang, T. Ditmire, M. Donovan, G. Dyer, E. Gaul, J. Gordon, M. Martinez, M. Spinks, T. Toncian, C. Wagner and M. C. Downer

Department of Physics, University of Texas at Austin, Austin, Texas 78712-1081, USA

(Dated: May 25, 2017)

We convert a GeV laser-plasma electron accelerator into a compact femtosecond-pulsed γ-ray source by inserting a 100μm-thick glass plate ~ 3 cm after the accelerator exit. With near-unity reliability, and requiring only crude alignment, this glass plasma mirror retro-reflected spent drive laser pulses (photon energy hωL = 1.17 eV) with > 50% efficiency back onto trailing electrons (peak Lorentz factor 1000 < γe < 4400), creating an optical modulator that generated ~ 10^6 γ-ray photons with sub-mrad divergence, estimated peak brilliance ~ 10^21 photons/s/mm^2/mrad^2/0.1% bandwidth and negligible bremsstrahlung background. The γ-ray photon energy Eγ = 4γ^2_e hωL, inferred from the measured γe on each shot, peaked from 5 to 85 MeV, spanning a range otherwise available with comparable brilliance only from large-scale GeV-linac-based high-intensity γ-ray sources.

Atomic nuclei are natural sources of MeV γ-ray radiation. However, electron accelerators can generate intense directional beams of MeV photons (known as “megavoltage x-rays” in some communities) for probing and manipulating the nucleus and for medical, industrial and homeland security applications. Broadband, unpolarized bremsstrahlung γ-ray beams, with photon energy E < Eγ < 25 MeV, generated in high-Z targets by MeV electrons from small linacs are now standard tools in treatment of deep cancers [1], sterilization of food and medical equipment, and cargo scanning [2]. A wider range of nuclear photonic applications demands polarized, quasi-monochromatic, and/or short-pulsed γ-ray beams — e.g. studies of astrophysical nucleosynthesis mechanisms [3]; non-destructive detection and assay of nuclear materials [4]; isotope-selective transmutation of long-lived fission products [5]; production of medical radionuclides [6]; pulsed radiolysis [7]; and efficient generation of ultrashort polarized positron bunches suitable for injection into advanced accelerators [8] — with some requiring photon energies up to ~ 80 MeV. To meet this demand, several GeV-class electron accelerator facilities dedicated to generating intense γ-ray beams via pulsed laser Compton scatter (LCS) — e.g. the High-Intensity γ-ray Source (Hi-γS) [9], NewSUBARU [10] and others [11] — have been built and operated starting in the 1980s, while new linac-based γ-ray sources featuring e.g. exceptional narrow width [12], high photon flux [13] and ultrashort pulse duration [14] continue to emerge. These facilities exploit the ability of LCS to map the polarization and spectral-temporal structure of the scattering laser pulse onto the γ-radiation. LCS generates the most energetic γ-rays in the backscatter geometry — for which Eγ = 4γ^2_e hωL, where γe is the electron Lorentz factor and hωL the laser photon energy [14]. Thus to generate 80 MeV γ-rays via backscatter of a standard Nd:YAG laser pulse (hωL = 1.17 eV) requires electrons with γe = 4.1 × 10^3 (energy E_e = 2.1 GeV).

Within the past 4 years, compact laser-plasma accelerators (LPAs) [15] have produced 2 to 4 GeV quasi-monoenergetic electron bunches [16][17] within an acceleration distance of centimeters — thousands of times smaller than conventional GeV linacs. In these LPAs, an ultrashort drive laser pulse of 0.3 to 0.6 PW peak power traversing cm-length tenuous plasmas blew out positively-charged, light-speed accelerating cavities of ~ 50μm diameter, which captured ambient plasma electrons at their rear and accelerated them in their internal GV/cm electrostatic fields to GeV energy. The emergence of GeV LPAs raises the intriguing possibility of developing small, easily accessible LCS γ-sources that span the photon energy range (1 < Eγ < 80 MeV) of linac-based LCS facilities, complementing their capabilities while more readily providing synchronized electron bunches and γ-ray pulses of fs duration [18]. Indeed the planned Extreme Light Infrastructure-Nuclear Physics (ELI-NP) facility is based on this possibility [19].

Previous work based on sub-GeV LPAs has already demonstrated Compton sources up to low-MeV photon energy. The simplest of these generated broadband [20] or tunable quasi-monochromatic [21][22] Compton backscatter x-rays with measured photon energy up to 2 MeV [23] by inserting a reflective film just after the exit of a < 450 MeV TW-laser-driven LPA. The film acted as a plasma mirror (PM) [24] that retro-reflected the intense part of the drive pulse onto trailing accelerated electrons, without alignment difficulty, while the generation of background bremsstrahlung x-rays from LPA electrons was suppressed by using a thin low-Z PM material [21][24]. However, this simple technique has not been scaled to GeV LPAs because their PW drive pulses possess stronger pre-pulses (requiring more stringent suppression techniques than TW pulses) that pre-expand the PM surface, degrading its reflectivity and the efficiency and reliability of Compton backscatter. Instead Compton photons above 2 MeV have been generated from LPAs by the more technically challenging approach of colliding the micrometer-sized LPA electron bunch with a separate
Scintillator signals with PM in place (top), showing Compton with a backscattering pulse focused to a erating quasi-monochromatic LCS photons up to 9 MeV. Some researchers successfully met these challenges, gen-

erating electrons that produced them with ±5% accuracy on every shot using a calibrated magnetic spectrometer [16]. From the relation \( E_e = 4\gamma_e^2\hbar\omega_L \), we inferred peak \( E_e \) spanning the entire range currently available from large-scale GeV-linac-based LCS sources [9, 10].

We carried out experiments at the Texas PW Laser [28, 29], which provided drive laser ("pump") pulses of 1.57 nm center wavelength, 150 fs duration, and energy between 75 and 110 J. Fig. 1a shows the setup. A spherical mirror focused the pulses in vacuum at \( f/40 \) into the entrance aperture of a 7-cm-long gas cell, which we filled uniformly with 6 Torr He gas immediately before each shot. The pulses fully ionized the gas, creating plasma of electron density \( n_e \approx 5 \times 10^{17} \text{ cm}^{-3} \), and generating self-injecting plasma bubbles that accelerated electrons to GeV energy [10]. The pump pulse transmitted through the accelerator reflected at 7° ± 2° from a PM (\( L = 100 \mu \text{m} \) thick fused silica), which we replaced after each shot. This geometry avoided retro-reflecting the pump into the amplifier chain. A probe pulse, generated by frequency-doubling a split-off portion of the pump, reflected at 45° simultaneously with the pump, and was imaged from the PM to a charge-coupled device (CCD) camera through

FIG. 1. Color online. (a) Schematic experimental setup for production and measurement of GeV electrons and Compton γ-rays: PM = plasma mirror; scint = pixelated scintillator. (b) Spatial profile of probe intensity \( I \) reflected from PM without (top) and with (bottom) excitation by the transmitted LPA drive pulse, with respect to peak intensity \( I_0 \) of incident probe. (c) Electron spectrum (left) with peak at 2.2 GeV and corresponding betatron x-ray profile (upper right) recorded on IP. Dark circles on betatron x-ray profile are thin metal converters (for γ-rays); x-ray energy analysis [33]; secondary particles from γ-ray conversion produced a bright spot near center of metal disk (lower right) on a separate shot. (d) Scintillator signals with PM in place (top), showing Compton γ-ray profile, and with no PM (bottom).
spectral filters that rejected scattered pump light.

An imaging plate (IP) located at \( z = 2.7 \text{ m} \) recorded magnetically-dispersed accelerated electrons, and keV betatron x-rays [31], after they passed through a 50 \( \mu \text{m} \) thick aluminum foil (not shown) that deflected any remaining drive pulse into a beam dump. Energy-dependent electron number \( dN_{e}/dE_{e} \) and total \( q \) were determined from measured photo-stimulated luminescence (PSL) levels scanned from exposed IPs, and quantified using a calibration procedure described in Ref. [16]. Compton \( \gamma \)-rays passed through PM, laser deflector, IP, and a 3.3-mm-thick Al back plate of the vacuum chamber (which blocked collinear betatron x-rays) before a pixilated CsI(Tl) \(^{+}\) scintillator detected them at \( z = 5.5 \text{ m} \). Calculations of \( \gamma \)-ray attenuation [32] show that secondary particles that the \( \gamma \)-rays generate in these materials account for \(< 3\% \) of the scintillator signal. The \( \gamma \)-rays alone left no discernible trace on the IP. However we covered \( \sim 6 \text{ cm}^2 \) of the IP with a planar array of forty 4 mm-diameter, 20-200 \( \mu \text{m} \)-thick disks of various metals (Fig. 1c, upper right). These characterized betatron x-rays [33], and on some shots, when a \( \gamma \)-ray pulse passed through one disk, converting a small fraction of its energy to secondary electrons (\( e^{-}\) and positrons (\( e^{+}\)) that did expose the IP (Fig. 1c, lower right), they allowed us to determine the number \( N_\gamma \) of photons in the pulse.

Figure 1b)-d) presents representative data. Figure 1b) shows images of the probe reflected from the PM without (top) and with (bottom) simultaneous irradiation by the spent LPA drive pulse. Within the 1-mm-diameter pump-irradiated region, PM reflectivity increased tenfold. Based on the size of the imaged high-reflectivity region, we conclude that the transmitted pump diverged at cone angle \( \theta_L \sim 30 \text{ mrad} \) (FWHM), and had intensity \( I \lesssim 4 \times 10^{17} \text{ W/cm}^2 \) (FWHM) on each PM.

Figure 1c) shows a magnetically dispersed electron spectrum (left) with a peak at \( E_e = 2.2 \text{ GeV} \) and angular divergence \( \theta_e \approx 0.9 \text{ mrad} \) (FWHM), and betatron x-rays (right) of angular divergence \( \theta_x \approx 6 \text{ mrad} \) (FWHM), recorded on the IP. Figure 1d) shows the \( \sim 5 \text{ mm} \) diameter spatial profile of \( \gamma \)-rays recorded on the 5 \( \times \) 5 cm scintillator (top), corresponding to angular divergence \( \theta_\gamma \approx 1 \text{ mrad} \). With the PM in place, we observed a signal of similar brightness and \( E_e \) from every shot that produced quasi-monoenergetic GeV electrons. With no PM, we observed no such signal (bottom), even for shots that generated copious GeV electrons. The diffuse signal at the left edges of the panels in d) is forward bremsstrahlung generated by the least magnetically-deflected (highest \( E_e \)) electrons in the vacuum chamber back plate. We observe this signal regardless of the presence of the PM.

Observed \( \gamma \)-ray signals that depend on the PM could be generated from GeV electrons either by forward bremsstrahlung radiation within the PM or by LCS in front of the PM. To distinguish these possibilities, we observed how the scintillator signal depended on \( L \), PM material, and intensity \( I_R(z) \) reflected from the PM.

Bremsstrahlung is proportional to \( L \) and increases for PM materials of higher \( Z \), but does not depend on \( I_R(z) \). LCS, on the other hand, does not depend on PM thickness or material, but is proportional to \( I_R(z) \), which we varied by adjusting the distance \( z \) over which the spent drive pulse diverged from accelerator to PM. This intensity in turn determined the PM reflectivity [30].

As an example, Fig. 2 compares scintillator signals from two shots driven by nearly identical laser pulses that yielded electron bunches spectrally peaked at \( E_e = 920 \pm 20 \text{ MeV} \) with total charge \( q = 50 \text{ (a) or 125 pC (b)} \). The integrated signals in Fig. 2a) and 2b), which were generated with glass PMs of \( L = 100 \text{ (a) or 180 } \mu \text{m (b)} \) located at \( z_a = 3.3 \text{ (a) or } z_b = 5.5 \text{ cm (b)} \), respectively, as illustrated at the top of Fig. 2, have the ratio \( S_b/S_a = 1.3 \). Normalized to \( q \), with which both bremsstrahlung and LCS scale linearly, the ratio becomes \( [S_b/S_a]_n = S_b/S_a \times q_a/q_b = 1.3 \times 0.4 = 0.52 \). Signals dominated by bremsstrahlung would have yielded \( [S_b/S_a]_n = 1.8 \text{ in view of the 1.8 } x \text{ thicker PM in case (b).} \)

On the other hand, signals originating mostly from LCS should yield \( [S_b/S_a]_n = I_R(z_b)/I_R(z_a) \). The estimated squared field strength \( a_0^2(z) \propto z^{-2} \text{ incident} \) on each PM was \( a_0^2(z_a) \approx 0.25 \) and \( a_0^2(z_b) \approx 0.09 \), which yield slightly different PM reflectivities \( R_a \approx 0.7 \) and \( R_b \approx 0.9 \text{ [30].} \)

Thus we expect \( I_R(z_b)/I_R(z_a) = (0.9/5.5^2)/(0.7/3.3^2) \approx 0.46 \), in good agreement with the observed \( [S_b/S_a]_n \). For comparison, the bremsstrahlung signal at the left-hand edge of panel (b) is \( 2.4 \times \) stronger than its counterpart in panel (a), a consequence of the \( 2.5 \times \) higher \( q \).

Analysis of other shots, and calculations, supported the conclusion that LCS dominated for our conditions. For example, a separate series of \( \sim 20 \text{ shots using low-} \text{Z (plastic) PMs with } L \text{ varying from 12.5 to 125 } \mu \text{m} \) yielded normalized scintillator signals similar to those in Fig. 2 with no discernible \( L \)-dependence. As a second example, the calculated bremsstrahlung energy loss of the 50 pC of electrons within the \( E_e \approx 2.2 \text{ GeV} \) (\( \Delta E_e^\text{FWHM} = 0.25 \text{ GeV} \)) peak in Fig. 1c traveling through \( L = 100 \mu \text{m} \) fused silica (density \( \rho_{SiO_2} = 2.5 \text{ g/cm}^3 \)) is \( E_{brems} = \alpha_\gamma \rho_{SiO_2} q L \approx 6.2 \times 10^{14} \text{ eV} \), where \( \alpha_\gamma \approx 80 \text{ MeV-cm}^2/\text{g} \) is the radiative stopping power of 2.2 GeV electrons in

![FIG. 2. Color online. Scaling of scintillator signal with position \( z \) and thickness \( L \) of PM: (a) \( z = 3.3 \text{ cm}, L = 100 \mu \text{m}; (b) } z = 5.5 \text{ cm, } L = 180 \mu \text{m.} \) Nearly identical laser pulses drove both shots; both yielded electrons with energy peaked at 0.92 GeV and corresponding charge (a) 50 or (b) 125 pC.](image_url)
The simulation toolkit GEANT4 \cite{34} yielded similar $E_{\text{brem}} \approx 7.4 \times 10^{14}$ eV, along with the spectrum in Fig. 3. For comparison, the spectral density of LCS within the observed solid emission angle $\Delta \Omega = 0.92 \mu\text{sr}$ (Fig. 1d, top) is \cite{35}

$$dN_\gamma / dE_\gamma \approx \alpha_f \frac{\gamma_e \alpha_0^2}{8\pi \alpha_L} \Delta \Omega \left[ \frac{dN_e}{dE_e} \right], \quad (1)$$

where $\alpha_f$ is the fine structure constant, and (for data in Fig. 1c,d) $\gamma_e = 4400$, $\alpha_0 \approx 0.3$ retro-reflected from the PM. Fig. 3b shows the resulting $dN_\gamma / dE_\gamma$ peaked at $E_\gamma = 85$ MeV with $\Delta E_\gamma^{(\text{FWHM})} = 18$ MeV. The FWHM contains $N_\gamma = 7.6 \times 10^6$ photons of total energy $\sum (N_\gamma \times E_\gamma) = 6.8 \times 10^{15}$ eV, about $11 \times$ the estimated bremsstrahlung yield in the PM. This supports the conclusion that most observed $\gamma$-rays originate from LCS. The entire $dN_e / dE_e$ in Fig. 1c generated a total $N_\gamma \approx 2 \times 10^6$ photons from $20 < E_\gamma < 100$ MeV.

We verified the accuracy of Eq. (1) for estimating $dN_\gamma / dE_\gamma$ by analyzing the secondary $e^-$ and $e^+$ energy distributions produced by 40 MeV $\gamma$-rays in converter that led to IP exposure in Fig. 1c (lower right).

We compared the accuracy of Eq. (1) for estimating $dN_\gamma / dE_\gamma$ by analyzing the secondary $e^-$ and $e^+$ energy distributions produced by 40 MeV Compton $\gamma$-rays that produced the IP excitation in Fig. 1c (lower right) upon passing through a Ag (75$\mu$m)/Cu (34$\mu$m) film pair. We input the $dN_\gamma / dE_\gamma$ from this shot (not shown), calculated from the measured $dN_e / dE_e$ via Eq. (1), into GEANT4, approximating it as a gaussian peaked at $E_\gamma = 40$ MeV with $\Delta E_\gamma^{(\text{FWHM})} = 20$ MeV. Upon passing through the converter, the simulated $\gamma$-ray pulse (total $N_\gamma \sim 10^7$) generated $e^-$ and $e^+$ energy distributions shown in Fig. 3, with total particle number $(N^-_e + N^+_e) \approx 1.28 \times 10^8$. We compared this with the total particle number $N_{IP}$ obtained directly from the measured PSL within the FWHM of the exposed spot in Fig. 1c, using published MS IP sensitivity $\approx 20 \pm 5$ mPSL/e \cite{36}. The result — $N_{IP} \approx 1.1 \pm 0.2 \times 10^5$ — agreed well with the simulated value.

FIG. 3. Color online. Calculated properties of $\gamma$-rays from PM. (a) GEANT4 calculation of bremsstrahlung spectrum produced by 2.2 GeV electrons in 100$\mu$m glass PM. (b) $dN_e / dE_e$ of 85 MeV Compton $\gamma$-rays, calculated from $dN_e / dE_e$ in Fig. 1c (left) and Eq. (1). (c) GEANT4 calculation of $\gamma$-ray energy distributions produced by 40 MeV $\gamma$-rays in converter that led to IP exposure in Fig. 1c (lower right).

Shamir et al. \cite{37} showed the resulting $dN_e / dE_e$ in Fig. 1c, using published MS IP sensitivity $\approx 20 \pm 5$ mPSL/e \cite{36}. The result — $N_{IP} \approx 1.1 \pm 0.2 \times 10^5$ — agreed well with the simulated value.

FIG. 4. Color online. Shot-to-shot pointing and divergence fluctuations. (a) Electron spectra and (b) $\gamma$ profiles, showing equal and opposite vertical angle displacements, and different horizontal displacements, on each of two shots.

Shot-to-shot fluctuations in the pointing and angular divergence of the Compton $\gamma$-ray beam closely tracked corresponding fluctuations of the GeV electron beam, and thus provided valuable e-beam diagnostics. As an example, Fig. 4 shows matching $\pm 1$ mrad $\gamma$-ray profiles, showing equal and opposite vertical angle displacements, and different horizontal displacements, on each of two shots.

We compared the accuracy of Eq. (1) for estimating $dN_\gamma / dE_\gamma$ by analyzing the secondary $e^-$ and $e^+$ energy distributions produced by 40 MeV $\gamma$-rays in converter that led to IP exposure in Fig. 1c (lower right).
pulse duration $\tau_p \approx 80$ fs (i.e. half a plasma period for $n_e \approx 5 \times 10^{27}$) and estimated source-size radius of 20 $\mu$m at $z = 3.3$ cm, we estimate peak-brilliance ranging from $(0.1-4.6) \times 10^{21}$ photons/s/mm$^2$/mrad$^2$ within 0.1% bandwidth. The highest number originates from the most energetic spectral peak in Fig. 5, whose $dN_e/dE_\gamma$ is presented in Fig. 4b.

Currently energy spread of our LPA electrons ($\Delta E_e^{(FWHM)} \sim 100$ MeV) limits $\Delta E_\gamma^{(FWHM)}$. However, LPAs have produced $\Delta E_e^{(FWHM)} < 3$ MeV at $E_e = 180$ MeV [39] and < 0.2 MeV at $E_e \lesssim 1$ MeV [40], using specialized injection methods. Simulations show such widths can be preserved to GeV energy [41]. Moreover, $a_0^2$ of the backscatter pulse (and thus $N_e$) can be increased approximately ten-fold, while LCS remains linear and PM reflectance high [39], by moving the PM closer to the LPA exit. These combined improvements could decrease $E_e$ (FWHM) to $\sim 0.1$ MeV, opening up nuclear spectroscopy applications, while increasing peak brilliance to $> 10^{25}$ photons/s/mm$^2$/mrad$^2$/0.1% bandwidth.

In summary, we converted a compact 0.5-2.2 GeV laser-plasma electron accelerator into a bright fs-pulsed, quasi-monochromatic Compton $\gamma$-ray source with peak photon energies tunable from 5 to 85 MeV by inserting a low-Z plasma mirror near the accelerator exit. We foresee such sources eventually complementing large linac-based LCS sources in nuclear photon research and applications.

DOE grants [de-sc0011617] and [de-sc0012444], AFOSR grant FA9550-14-1-0045 and NNSA Cooperative Agreement [de-na0002008] supported this work. KW was supported by Computational Sciences Graduate Fellowship under DOE grant DE-FG02-97ER25308.

---

1) Present address: Institute for Radiation Physics, Helmholtz-Zentrum Dresden-Rossendorf, Germany.

[1] S. H. Levitt, J. A. Purdy, C. A. Perez, and P. Poortmans, "Physics of Radiotherapy Planning and Delivery", in Technical basis of radiation therapy practical clinical applications, 5th ed. (Heidelberg, Springer 2012), p. 96.

[2] R. W. Hamm and M. E. Hamm, Industrial accelerators and their applications (Singapore, World Scientific 2012).

[3] T. Hayakawa et al., Phys. Rev. C 74, 065802 (2006).

[4] R. Hajima, Nucl. Instrum. Methods Phys. Res. A 608, S57 (2009).

[5] D. Li, K. Imasaki, K. Horikawa, S. Miyamoto, S. Amano and T. Mochizuki, J. Nucl. Sci. Tech. 46, 831-835 (2009); H. Ejiri et al., J. Phys. Soc. Japan 80, 094202 (2011); T. Hayakawa et al. J. Nucl. Sci. Tech. 53, 2064 (2016).

[6] D. Habs and U. Köster, Appl. Phys. B 103, 501 (2011).

[7] Y. Taira et al. Nucl. Instrum. Methods Phys. Res. A 647, S1 (2011).

[8] D. Li, K. Imasaki, S. Miyamoto, K. Horikawa, S. Amano and T. Mochizuki, Appl. Phys. Lett. 94, 091112 (2009); W. Luo, H. B. Zhuo, Y. Y. Ma, X. H. Yang, N. Zhao and M. Y. Yu, Laser and Particle Beams 31, 84 (2013).

[9] H. R. Weller et al., Prog. Part. Nucl. Phys. 62, 257 (2009).

[10] S. Amano et al., Nucl. Instrum. Methods Phys. Res. A 602, 337 (2009).

[11] A. D’Angelo et al., Nucl. Instrum. Methods Phys. Res. A 455, 1 (2000).

[12] F. Albert et al., Phys. Rev. ST-Accel. Beams 14, 057003 (2011).

[13] R. Hajima, T. Hayakawa, N. Kikizawa and E. Minehara, J. Nucl. Sci. Tech. 45, 441 (2008).

[14] E. Esarey, S. K. Ride and P. Sprangle, Phys. Rev. E 48, 3003 (1993).

[15] E. Esarey, C. B. Schroeder, W. P. Leemans, Rev. Mod. Phys. 81, 1229–1285 (2009).

[16] X. Wang et al., Nature Commun. 4, 1988 (2013).

[17] H. T. Kim et al., Phys. Rev. Lett. 109, 165002 (2013); W. P. Leemans et al., Phys. Rev. Lett. 113, 245002 (2014).

[18] F. V. Hartemann et al., Phys. Rev. ST-Accel. Beams 10, 011301 (2007).

[19] D. Habs, T. Tajima and V. Zamfir, Nucl. Phys. News 21, 23 (2011).

[20] K. Ta Phuoc et al., Nat. Photon. 6, 308 (2012).

[21] H.-E. Tsai et al., Phys. Plasmas 22, 023106 (2015).

[22] A. Döpp et al., Plasma Phys. Control. Fusion 58, 034005 (2016).

[23] Changhai Yu et al., Sci. Rpts 6, 29518 (2016).

[24] M. Geissel et al., Rev. Sci. Instrum. 85, 053101 (2011).

[25] S. Chen et al., Phys. Rev. Lett. 110, 155003 (2013); N. D. Powers et al., Nat. Photon. 8, 28 (2014).

[26] C. Liu et al., Opt. Lett. 39, 4132 (2014).

[27] G. Sarri et al., Phys. Rev. Lett. 113, 224801 (2014).

[28] E. Gaul et al., Appl. Opt. 49, 1676 (2010).

[29] E. Gaul et al., J. Phys.: Conf. Series 717, 012092 (2016).

[30] H.-E. Tsai et al., Phys. Plasmas 24, 013106 (2017).

[31] A. Rousse et al. Phys. Rev. Lett. 93, 135005 (2004).

[32] http://physics.nist.gov/PhysRefData/Star/Text/method.html

[33] N. Fazel et al. AIP Conf. Proc. 1777, 080005 (2016).

[34] J. Allison, IEEE Trans. Nucl. Sci. 53, 270 (2006).

[35] H. Schwoerer, B. Liesfeld, H.-P. Schlenvoigt, K.-U. Amthor, and R. Sauerbrey, Phys. Rev. Lett. 96, 014802 (2006).

[36] N. Rabhi et al., Rev. Sci. Instrum. 87, 053306 (2016).

[37] C. E. Clayton et al., Phys. Rev. Lett. 105, 150503 (2010).

[38] K. Chouffani, F. Harmon, D. Wells, J. Jones, and G. Lancaster, Phys. Rev. ST-Accel. Beams 9, 050701 (2006).

[39] C. Rechatin et al. Phys. Rev. Lett. 102, 164801 (2009).

[40] C. G. R. Geddes et al., Phys. Rev. Lett. 100, 215004 (2008).