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Ultrashort-pulse MeV positron beam generation from intense Compton-scattering γ-ray source driven by laser wakefield acceleration

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Abstract

Intense Compton-scattering γ-ray radiation driven by laser wakefield acceleration (LWFA) and generation of ultrashort positron beams are investigated by Monte Carlo simulation. Using an LWFA driven GeV electron bunch and a 45 femtosecond, 90 mJ/pulse, and 10 Hz Ti:Sapphire laser for driving the Compton scattering, fs γ-ray pulses were generated. The latter have a flux of $\geq 10^8$/s, peak brightness of $\geq 10^{20}$ photons/(s mm^2 mrad^2 0.1% bandwidth), and photon energy of 5.9 to 23.2 MeV. The γ-ray pulses then impinge on a thin high-*Z* target. More than 10^7 positrons/s in the form of sub-100 fs pulses at several MeV can be produced. Such ultrashort positron pulses can be useful as the pump-probe type positron annihilation spectroscopy as well as in other applications.

Keywords: Compton scattering; Femtosecond *γ*-ray pulse; Laser wakefield acceleration; Positron beam; Ultrashort

1. INTRODUCTION

To create large numbers of MeV positrons in the laboratory is of considerable research and application interest. Novel positron sources are needed for the electron-positron linear collider (Hirose *et al.*, 2000), nuclear medicine (Raichle *et al.*, 1985), and as diagnostic tools. For example, positron annihilation spectroscopy (PAS) is a valuable tool in materials research, atomic physics, as well as condensed matter physics (Mills *et al.*, 1982; Schultz *et al.*, 1988; Hunt *et al.*, 1999; Gidley *et al.*, 2006). PAS makes use of slow positrons from radioactive sources or from pair production through energetic beam-target interaction. Shortening the positron pulses can increase the accuracy of PAS (Jean *et al.*, 2003), and can open a door for pump-probe type PAS applications for investigating ultrafast dynamics in material and biological structures.

Several schemes for generating positron beams have been proposed (Surko *et al.*, 1989; Liang *et al.*, 1998; Cowan *et al.*, 1999; Andreev *et al.*, 2000; Kurihara *et al.*, 2000; Shen *et al.*, 2002). Positrons can be obtained from β^+ emitters (Surko *et al.*, 1989) and large-scale facilities such as linear electron accelerators (linacs) (Kurihara *et al.*, 2000), as well as nuclear reactors (Hugenschmidt *et al.*, 2008). Continuous positron sources from beta decay have limitations such as low intensity and relatively wide angular distribution. Positron beams from linacs can have intensities up to 10^8/s, but they are of long duration, namely on the order of tens picoseconds. Intense relativistic picosecond positron beams at $\geq 2 \times 10^{10}$ positrons/s can be obtained from laser-solid interactions with lasers capable of 10^2–10^3 J/shot (Chen *et al.*, 2011), which is at present still rare. In addition, Taira *et al.* (2010) proposed picoseconds positron beam generation from laser-Compton γ rays at 90° collision geometry.

Since the development of high-power tabletop lasers (Perry *et al.*, 1994), particle accelerators based on the interaction of ultrashort ultraintense (USUI) laser pulses with plasmas, in particular, laser wakefield acceleration (LWFA) (Tajima *et al.*, 1979), can be realized. LWFA can generate several hundred GeV/m electric fields and deliver high-quality relativistic ($\geq$100 MeV), up to 0.5 nC, electron beams. The latter also have low (few percent) energy spread, small (few mrad) spatial divergence, and short (few

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femtosecond) pulse duration (Mangles *et al.*, 2004; Geddes *et al.*, 2004; Faure *et al.*, 2004; 2006; Leemans *et al.*, 2006; Lundh *et al.*, 2011). They are therefore useful to some tunable sources of ultrashort radiation, such as the laser-Compton light source (Catravas *et al.*, 2001; Schwoerer *et al.*, 2006; Phuoc *et al.*, 2012).

In this paper, we propose a scheme for generating ultrashort positron beams by irradiating femtosecond γ-ray pulses (GRPs) obtained from Compton scattering off a thin metal target. The scheme is illustrated schematically in Figure 1. Since the head-on collision geometry is used for the Compton scattering, the GRP duration only depends on the (very short) length of the LWFA electron bunch, thereby eliminating the need (a key issue in current linacs or storage rings) for shortening the electron bunches. It is found that GRPs with average flux of 10^8/s can be obtained, and MeV positrons at over 10^7/s can be produced on a sub-100 fs time scale. In practice, such a positron source would be much compacter than the current linac or reactor based sources.

2. LWFA-DRIVEN FEMTOSECOND GRP

2.1 Principle

Compton scattering has been proposed as a means of generating tunable, short pulses of X/γ rays with narrow bandwidth (Hartemann *et al.*, 2004; Chouffani *et al.*, 2006; Luo *et al.*, 2010). The most intense Compton scattered photons are produced when the laser light is backscattered off the electrons. For such head-on interaction geometry, the energy of the scattered photon is given by

$$E_P \approx \frac{4\gamma^2 E_L}{1+\gamma^2\theta^2+4\gamma^2 E_L E_e}, \tag{1}$$

where E_L and E_e are the energies of incident photon and electron, respectively, γ is relativistic factor of the electron, and θ is the scattering angle relative to the electron trajectory. Accordingly, scattering of 800 nm (Ti:Sa) laser light off a 1 GeV LWFA produced electron bunch can generate a ≥20 MeV GRP. Considering the small divergence and narrow energy spread of the LWFA driven electron bunch, the on-axis spectral broadening of GRP for sufficiently small laser bandwidth and divergence can be roughly given by

$$\frac{\Delta E_P}{E_p} \sim \sqrt{\frac{\gamma^4(\Delta\xi_{xe}^2+\Delta\xi_{ye}^2)^2}{4}+\frac{4\Delta\gamma^2}{\gamma^2}+\frac{(\Delta\xi_{xL}^2+\Delta\xi_{yL}^2)^2}{4}+\frac{\Delta E_L^2}{E_L^2}}, \tag{2}$$

where $\Delta\gamma/\gamma$ and $\Delta E_L/E_L$ are the energy spreads of the electron beam and laser pulse, ξ_{xe} and ξ_{ye} are the transverse (in the x and y directions, respectively) emittance of the electron beam, ξ_{xL} and ξ_{yL} are the effective $(1/e^2)$ transverse emittance of the focused laser beam, using the analogy of the Rayleigh range to the beta function of a particle beam focus (Brown *et al.*, 2004), $\Delta\xi_{xe,ye}$ and $\Delta\xi_{xL,yL}$ are the $1/e^2$ divergence of the electron beam and laser pulse. The latter are both assumed to be Gaussian and narrow. It should however be emphasized that the GRP distribution is usually non-Gaussian, so that its spectral bandwidth should better be determined from the final energy spectrum after convolution with the distributions of the laser and electron beam parameters causing the broadening. On the other hand, the estimates in Eq. (2) should be applicable to the on-axis (or very small solid angle) γ rays.

The duration τ_p of the Compton-scattering GRP is determined by the interaction time of the electron and laser beams. For head-on collision, it is (Pogoelsky *et al.*, 2000)

$$\tau_p = \tau_e + \tau_L/4\gamma^2, \tag{3}$$

where τ_L and τ_e are the durations of the laser pulse and the electron beam, respectively. Thus, LWFA electron bunches

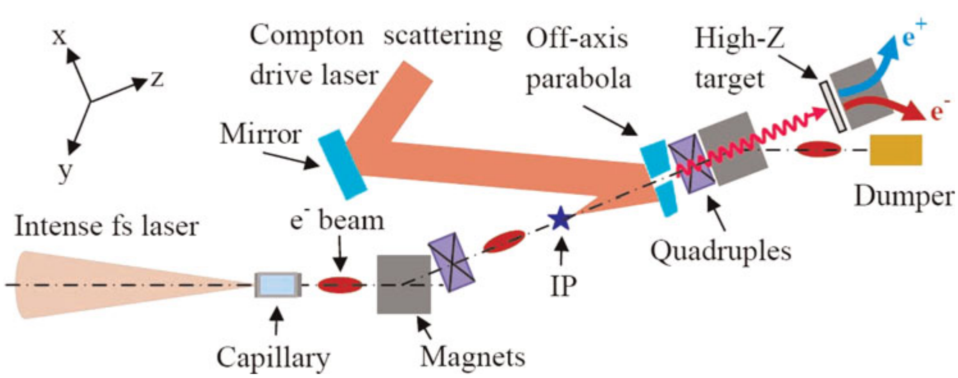

Fig. 1. Schematic illustration of positron generation via Compton scattering of laser light off LWFA electron beams (e^- beams) and the resulting pair creation. An USUI pump laser is focused onto a gas-filled capillary-discharge waveguide or gas jet to generate an LWFA electron bunch. The X/γ rays are then generated by colliding the USUI electron bunch from LWFA with the light from a TW laser that drives the Compton scattering. After passing through the off-axis parabola, the Compton backscattered γ rays impinge on a thin high-Z target to generate an ultrashort positron pulse.

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of sufficiently short duration can be used to generate fs GRPs.

For spatially overlapped and synchronized Gaussian laser pulse and electron beam of sufficiently small energy spread and emittance, the scattered photon flux can be approximately given by

$$N_p = \frac{f\,\sigma N_e N_L}{2\pi\sqrt{\sigma_{ye}^2+\sigma_{yp}^2}}\frac{1}{\sqrt{\begin{array}{l}(\sigma_{xe}^2+\sigma_{xp}^2)(1-\cos\theta_L)^2\\ +(\tau_e^2+\tau_L^2)c^2\sin^2\theta_L\end{array}}}, \quad (4)$$

where f is the laser and electron collision repetition rate, σ is the Compton scattering cross section, N_e is the number of electrons in the bunch, N_L is the total number of photons in the laser pulse, θ_L is the laser incident angle with respect to the electron beam, the subscripts e and p denote electrons and laser photons, respectively, and $\sigma_{x,y}$ are the transverse beam sizes of the laser pulse.

2.2 Characterization of fs GRP from the LWFA

To investigate the spatial, temporal, and spectral characteristics of Compton scattering X/γ-ray sources, a 4D (three dimensional time and frequency domain) Monte Carlo laser-Compton scattering simulation (MCLCSS) code (Luo *et al.*, 2011) has been developed with the Geant4 toolkit (Agostinelli *et al.*, 2003). The code is used to investigate the properties of the USUI GRPs from the LWFA. The electron-bunch parameters given in Table 1 correspond to the LWFA experiments at the Lawrence Berkeley National Laboratory (Leemans *et al.*, 2006). For comparison, the parameters of current synchrotron radiation facilities are also given. Electron energies up to 1.0 GeV are of particular interest, since they can yield MeV to tens MeV γ rays, which are needed for pair production on the femtosecond time scale, as well as for other applications such as nondestructive assay of nuclear fuel, waste, and specific nuclide using nuclear resonance fluorescence.

Figure 2a shows the total γ-ray energy spectrum obtained from the Monte Carlo simulations. For the LWFA driven electron beam with energies of 1.0 (0.5) GeV, the average on-axis γ-ray energies equal to about 23.2 (5.9) MeV. Since an infinitely small collimation angle is employed, the γ-ray spectral broadening is calculated to be about 6.0% at 23.2 MeV based on Eq. (3). The total (at all frequencies and angles) γ-ray dose is about 1.06×10^7 photons. From Eq. (4), one see that for a 10 Hz laser-electron collision repetition rate the flux of the resulting GRP is 1.06×10^8 photons/s, with the peak flux exceeding 4×10^{20} photons/s. When the 1.0 GeV LWFA driven electron beam is used, the corresponding peak γ-ray brilliance can be up to 10^{20} photons/s/mm^2/mrad^2/0.1%bandwidth.

Figure 2b shows that a 10-fs LWFA electron bunch can produce a similarly short GRP. Although at present the experimental measurement of ultrashort GRP remains an

Table 1. *LWFA driven electron beam parameters (Leemans* et al.*, 2006) and Ti:Sa laser-pulse parameters used in the simulation. For comparison, the key parameters of typical linac-based storage rings are also shown*

Parameter	LWFA	Linac-based storage ring
Electron energy E_e	0.5–1.0 GeV	≥1.0 GeV
Acceleration gradient	≥10 GeV/m	≤100 MeV/m
Bunch charge Q	50 pC	500 pC
Bunch length τ_e	<10 fs	10 ps
Natural emittance ε	~5 nm-rad	≤10 nm-rad
Bunch size $\sigma_{xe,ye}$	2–3 μm	100 μm
Energy spread Δγ /γ	2–5%	0.1%
Laser-electron timing jitter	Femtosecond	picosecond
Ti: Sa laser (Compton scattering drive laser)		
Laser wavelength λ_L	800 nm	
Total energy	90 mJ/pulse	
Pulse duration τ_L	45 fs	
Transverse size $\sigma_{xp,yp}$	10 μm	
Repetition rate f	10 Hz	
Normalized vector potential a_0	~0.25	

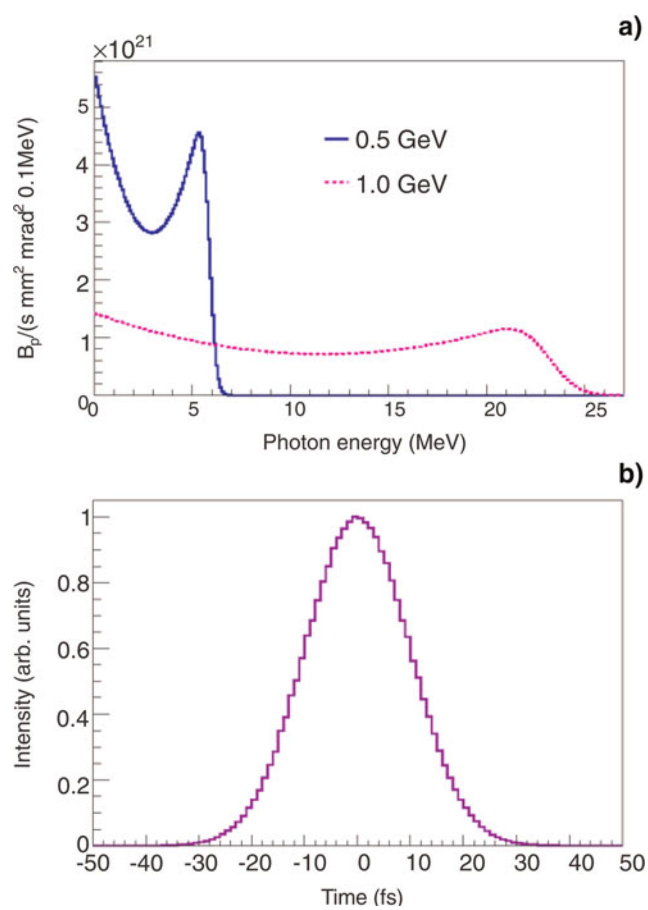

Fig. 2. (**a**) Total energy spectrum obtained from the MCLCSS code. (**b**) Temporal profile of the GRP obtained from a Gaussian LWFA electron bunch. The LWFA driven electron beam parameters are: 50 pC charge, 5 nm-mrad emittance, 3 μm (rms) spot sizes, and 2.5% energy spread.

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issue, besides useful for pair production on the femtosecond time scale, such short-pulse GRPs are of interest to applications such as pulse radiolysis since the properties of the scattered GRP is fully determined by the temporal profile of LWFA electron bunch and the GRP can yield fast time resolved information on the latter.

3. ULTRA-SHORT MeV POSITRON BEAM GENERATION

To produce positron-electron pairs, the energy of the scattered photons must be larger than the threshold $E_0 = 1.022$ MeV. For $m_ec^2 \ll E_p < 137 m_ec^2 Z^{-1/3}$, the cross section for pair production is (Rossi, 1952)

$$\sigma_{\text{pair}} = \sigma_0 Z^2 \left[\frac{28}{9}\ln\left(\frac{2E_p}{m_ec^2}\right) - \frac{218}{27}\right], \tag{5}$$

where $\sigma_0 = 5.8 \times 10^{-28}$ cm^2, Z is the atomic number, and m_ec^2 is the electron rest energy. Since the cross section of the pair production is proportional to Z^2, high-Z material should be used.

We use the Monte Carlo code Geant4 to determine the electron-positron pair production (emission) rate for several high-Z materials including Pt, W, and Pb. It is found that the Pb target results in maximum pair yield. Figure 3 shows that the optimum target thickness for pair production is about 4 mm, corresponding to a maximum generation rate of about 0.10 per γ-ray photon. For the γ-ray flux of 10^8/s mentioned earlier, one can expect an emission flux of 10^7 positrons/s in the form of a relativistic positron beam with about 20° divergence angle. Thus, about 3×10^7 positrons per unit solid angle may be achieved.

The duration of the positron pulse depends mainly on the target thickness and the duration of the GRP. As shown in Figure 3, a thinner target will result in shorter positron pulse duration. When a 4-mm-thick Pb plate is irradiated, the root mean square bunch length of the positrons can be as short as 166 fs. If one decreases the thickness of Pb plate to less than 2 mm, a sub-100 fs ultrashort positron bunch of considerable charge can be obtained. In practice, the bunch duration can be longer because of its interaction with the nuclei or the outer electrons via multiple scattering, ionization, and bremsstrahlung, but it is still shorter than that from the existing position sources by at least one order of magnitude.

Figure 4 shows the evolution of the energy spectrum of the emitted positrons. It has a peak at around 7 MeV. The energy spectrum of the electrons has a similar peak. However, the total electron flux (the green-circle curve in Fig. 3) is always higher than the positron flux (the blue-square curve in Fig. 3). This is to be expected, since the electrons are from both Compton scattering and pair creation, but the positrons are only from the latter.

4. SUMMARY

In this paper, a scheme for generating ultrashort positron bunches using moderate-flux short-pulse γ-ray radiation is proposed. The GRP is generated by Compton scattering of laser light off an USUI LWFA driven electron beam. The GRP is then impinged on a thin metal target to realize pair production and the energetic positron bunch. It is shown that from a 1 GeV, 50 pC, and 10 fs LWFA electron bunch, femtosecond GRP with a flux of 10^8/s can be obtained. By optimizing the thickness of the Pb target, more than 10^7 positrons/s in 100 fs pulses at peak energies of about 7 MeV can be obtained. Energetic positrons with even higher fluxes can be expected if a higher charged,

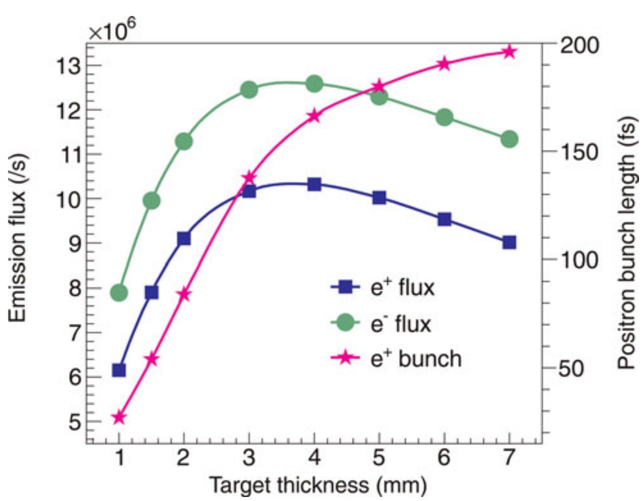

Fig. 3. Total positron flux and the corresponding bunch length as a function of the target thickness, from Monte Carlo simulation with the Geant4 toolkit. The calculation is for the spectrum (dotted curve) in Figure 2a.

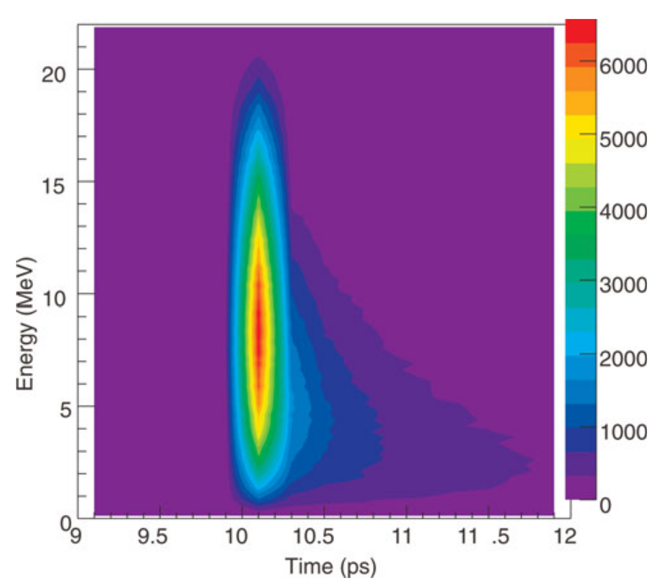

Fig. 4. Evolution of the positron spectrum, obtained from Monte Carlo simulation. The calculation corresponds to the spectrum given by the dotted curve shown in Figure 2a, for a 4 mm lead target.

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such as the ≥160 pC pulse from the electron bow-wave injection Scheme (Ma *et al.*, 2012), electron bunch is used to generate the GRP.

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