Storage-ring-based, ultrashort positron beam source

Yuelin Li,[a] Weiming Guo, and Katherine Harkay
Accelerator Systems Division, Argonne National Laboratory, Argonne, Illinois 60439

Wanming Liu
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

(Received 13 February 2006; accepted 24 May 2006; published online 13 July 2006)

We propose a scheme to generate high-flux, short-burst γ-ray radiation and its application for generating ultrashort positron beams. The intense γ-ray bursts are generated from short laser pulses scattering off high-energy electron beams in a storage ring. The γ-ray bursts are then used to irradiate thin metal targets to generate the positron beams via pair production. Using the example of the Advanced Photon Source storage ring, more than 10^7 positrons/s in 1 ps pulses at energies of a few MeV can be generated. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2221503]

Positron sources are used for medical imaging and as scientific research tools. Among the scientific applications, positron annihilation spectroscopy (PAS) is a very valuable tool in atomic physics, materials science, and solid state physics.[1] PAS uses slow positrons normally obtained from radioactive sources or from pair production through an energetic beam entering a target as either continuous or long pulse source.[2] Shortening the positron pulses can increase the accuracy of positron annihilation lifetime spectroscopy,[1] and may open the door for pump-probe-type PAS applications to study the ultrafast dynamics in material and biological structures.

In this letter, we propose a scheme for generating ultrashort positron beams. The scheme is based on generating a short γ-ray burst via small-angle Compton scattering[3] of laser pulses from the high-energy electron beams in a storage ring. The γ-ray burst is in turn impinged on a target to generate positrons with comparable pulse duration. Because of this small-angle scattering geometry, the γ-ray burst duration only depends on the laser pulse duration, hence eliminating the need for short electron bunches in the head-on scattering scheme.[4] Meanwhile, due to the relatively low γ-ray photon energy in comparison with that of the stored beam, the impact on storage ring operation is negligible. In our example, an average photon flux of 10^9/s can be obtained, giving positron production of over 10^7/s at an energy of about 2 MeV. We note that γ-ray pair production has also been adapted for positron sources for linear colliders.[5,6]

The small-angle Compton scattering scheme has been described in detail in Ref. 3. Briefly, when a laser pulse collides with an electron beam at an angle $\phi \ll 1$, for a relativistic factor $\gamma \gg 1$, the energy of the scattered photon is

$$E \approx E_L \frac{2\gamma^2}{1+\gamma^2\theta^2}(1-\cos\phi). \tag{1}$$

Here E_L is the energy of the incident photon and θ is the scattered angle with respect to the electron propagation direction. When $\theta=0$, we have $\phi=(E/E_L)^{1/2}/\gamma$. Using the Advanced Photon Source storage ring[7] as an example, $\gamma=13\,699$ and we have $\phi=0.13$ rad for $E=5$ MeV for a Ti:Sa laser at 800 nm or 1.55 eV of photon energy. Assuming that the laser beam waist matches the vertical size of the beam σ_y, the pulse duration of the scattered photons is determined by the laser pulse duration and the time required for the laser to traverse the electron beam,

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

For $\sigma_x=91.8$ μm and $\sigma_y=25.5$ μm, a laser pulse duration of $\tau_L \sim 100$ fs can be preserved. The total number of scattered photons is estimated as

$$N \approx \frac{\Sigma_0}{4\pi}\frac{N_e N_p}{\sigma_y\sigma_z}\phi. \tag{3}$$

Here Σ_0 is the total scattering cross section, N_e and N_p are the total numbers of electrons and photons in the beams, and σ_y and σ_z are the rms electron beam height and length. The laser beam and the electron beam are both propagating in the x plane. Note that scattering efficiency is proportional to the crossing flux or the crossing velocity between the two beams; therefore when $\phi \to 0$, we have $N \to 0$, as shown in Eq. (3).

To evaluate the performance of such γ-ray sources, we conducted the numerical simulations described in Ref. 3 using the laser and beam parameters in Table I. The average spectral flux is given in Fig. 1(a) with peak photon energy at 5 MeV. It gives $\sim$1400 γ-ray photons per interaction with a collection angle of $1/\gamma$. This is 5.5×10^6photons/s at 4 kHz. Using an optical cavity can trap the laser pulse for repetitive use. With a round-trip time matching that of the beam rate of 6.52 MHz, a cavity can enhance the average photon flux by a factor equivalent to the quality factor Q of the cavity. For

TABLE I. Advanced Photon Source Beam parameters and the laser pulse parameters.

	Beam	Laser
Electron, photon numbers per pulse	10^{11} (15 nC)	2×10^{16} (5 mJ)
Electron, photon energy	7 GeV	1.55 eV
Energy spread (rms)	0.1%	0.5%
Pulse duration	45 ps	0.1–1 ps
Repetition rate	6.528 MHz	4 kHz adjustable
rms beam size	92×26 μm^2	26×26 μm^2

[a]Electronic mail: ylli@aps.anl.gov

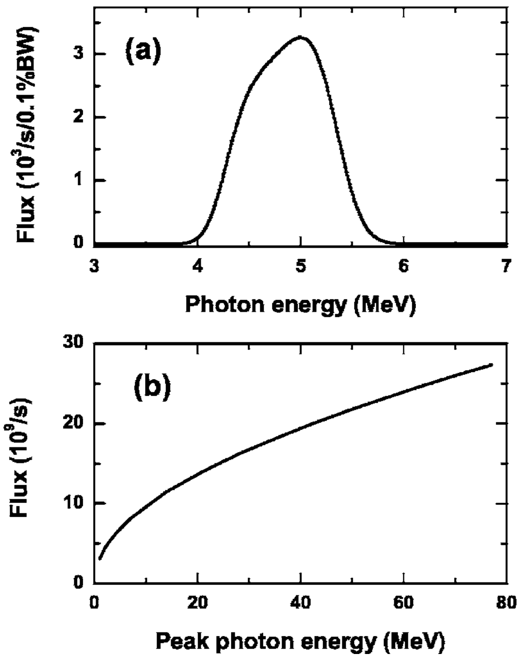

FIG. 1. (a) A γ-ray spectrum peaked at 5 MeV. (b) The total flux as a function of the peak photon energy. An acceptance angle of $1/\gamma$ is used in the calculation, where γ is the relativistic factor of the beam. The crossing angle is 0.13 rad. In (b), the peak photon energy is tuned by changing the interaction angle between the laser and the electron beam. Here a laser repetition rate of 4 kHz and an optical cavity with a quality factor of 1000 at 6.52 MHz are considered.

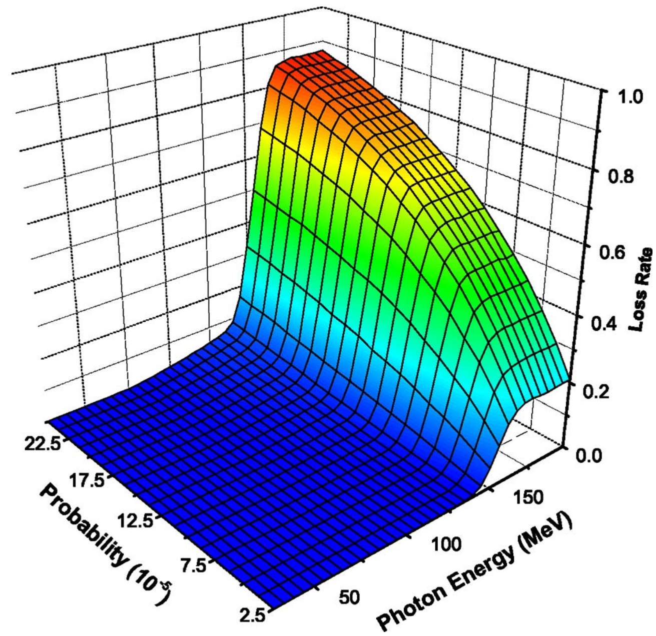

FIG. 2. (Color online) Electron loss as a function of γ-ray photon energy and the radiation probability per turn. Note the thresholdlike behavior at photon energy of about 140 MeV.

$Q=1000$, the flux is increased to 5.5×10^9/s. The total photon flux with this arrangement as a function of the peak photon energy is given in Fig. 1(b).

For this scheme to be practical, the impact on the dynamics of the stored electron beam must be negligible. In case the electron energy loss to the photon is well within the energy aperture of the storage ring, it stays in the rf bucket and the amplitude damps due to radiation damping.[8] However, due to this noiselike excitation, the ensemble of electrons will reach a new equilibrium. The new energy spread is

$$\sigma_\delta^2 = \sigma_{\delta,0}^2 + \frac{1}{4}\tau_E f P \frac{\langle E_p^2\rangle}{E^2}. \tag{4}$$

Here σ_δ and $\sigma_{\delta,0}=0.1\%$ are the equilibrium and the initial energy spread of the beam, respectively, τ is the longitudinal (energy) damping time of the beam, f is the excitation frequency, and P is the probability of excitation, which equals the ratio of the γ-ray photon number to the total electron number in the bunch. E_p is the photon energy and E is the electron beam energy. For the Advanced Photon Source (APS), $\tau=4.8\times 10^{-3}$ s and $f=272$ kHz (revolution frequency). From the above calculation, we have $P<10^{-7}$, corresponding to 10^4 γ-ray photons per turn. For 5 MeV photons, the second term in Eq. (4) is 1.6×10^{-11}, much smaller than the first term at 10^{-6}. For a 10% impact on σ_δ, P must be larger than 10^{-4}, equivalent to a photon emission of 10^7 per interaction.

The horizontal motion of the beam is also perturbed if the emission occurs at a dispersive location. The equilibrium emittance is

$$\varepsilon_x = \varepsilon_{x,0} + \frac{1}{4}\tau_x f P H \frac{\langle E_p^2\rangle}{E^2}. \tag{5}$$

Here ε_x and $\varepsilon_{x,0}=2.5$ nm are the equilibrium and the initial emittance, respectively, τ_x is the transverse damping time, and H is the dispersion action lattice function at the interaction point. For our case, $\tau_x=9.6\times 10^{-3}$ s, $H\sim 2$ mm, we again need $P>10^{-4}$ to introduce a 10% effect on ε_x. The photon emission does not affect the vertical motion of the beam.

The above results are confirmed by a one-dimensional (1D) particle-in-cell simulation. The simulation further reveals that a synchrotron like the APS can support much higher photon energy at higher photon flux without inducing particle loss (see Fig. 2). We note that the photon emission perturbation is similar to the energy modulation in the femtoslicing for ultrafast x-ray generation in a storage ring, which has been studied theoretically and experimentally recently.[9,10]

The positrons are generated via pair production in the nuclear field of the target atoms. For monochromatic γ rays, the total production is

$$M = \alpha_p \int_0^T e^{-\alpha_t x} dx = \frac{\alpha_p}{\alpha_t}(1-e^{-\alpha_t T}). \tag{6}$$

Here M is the total production of positrons per γ-ray photon, α_t is the total absorption coefficient of the γ ray, α_p is the production coefficient in the target, and T is the target thickness. For tungsten, $\alpha_t=0.76$ cm^{-1} and $\alpha_p=0.38$ cm^{-1} at 5 MeV photon energy,[11] giving total positron yields of 0.036, 0.071, and 0.13 positrons per photon for 1, 2, and 4 mm targets, respectively. Some of those positrons will be emanated from the target and some of them will be trapped and "load" the target.

We used the EGS4 Monte Carlo code[12] to determine the production, trapping, and emission rates for tungsten targets, which are shown in Fig. 3 as functions of the target thickness

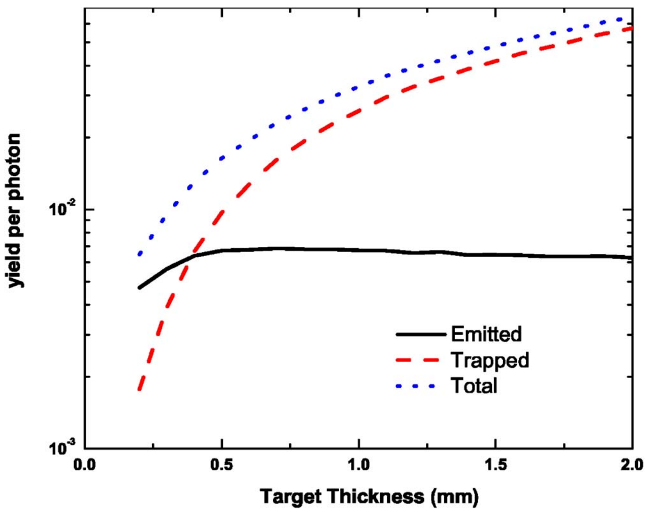

FIG. 3. (Color online) Total, trapped, and emitted positron yields per photon as functions of target length by EGS4 Monte Carlo simulation. The calculation is for the spectrum in Fig. 1(a).

using the spectrum in Fig. 1(a). While the total positron yield per photon increases monotonically with the target thickness, the number of positrons emanated maximizes at a thickness of 0.7 mm, giving 0.0069 positrons per photon. The trapping or loading is 0.016 positrons per γ-ray photon. With the γ-ray flux of 5.5×10^9/s given earlier, one expects an emission flux of 4×10^7/s and a loading of 9×10^7/s. It is possible to further increase the positron production by increasing the γ-ray photon energy. Simulation shows, at 49 MeV of peak photon energy, the photon flux increases to 2.2×10^{10}/s with the same laser and beam parameters, resulting in a positron yield of 0.114/photon and an emission flux of 2.5×10^9/s at energies up to 25 MeV for a 1 mm tungsten target. Note that those numbers are highly dependent on the target material.

The positron bunch length closely follows that of the laser pulse duration. Figure 4 gives the emission spectrum of the positions from the target as a function of time. The bunch length is 1.2 ps, while the laser pulse duration is 1 ps.

In general, these positrons emitted from the target are more energetic than those used in most PAS experiments. However, higher beam energy can provide larger probing depths, and applications of such "fast" PASs have been discussed.[13] These studies include time resolved measurement of the defect formation in refractory metals in high temperature equilibrium and semiconductor at near melting temperatures, melts of metals and semiconductors, and spin relaxation of positron in ferromagnets. In addition, trapping of the positrons in targets provides a mechanism to load the sample with positrons in a very short time, making it favorable for fast "*in situ*" PAS schemes. Above all, due to the short bunch length of the positrons, a pump-probe type of PAS experiment is possible for investigating the dynamics in the sample.

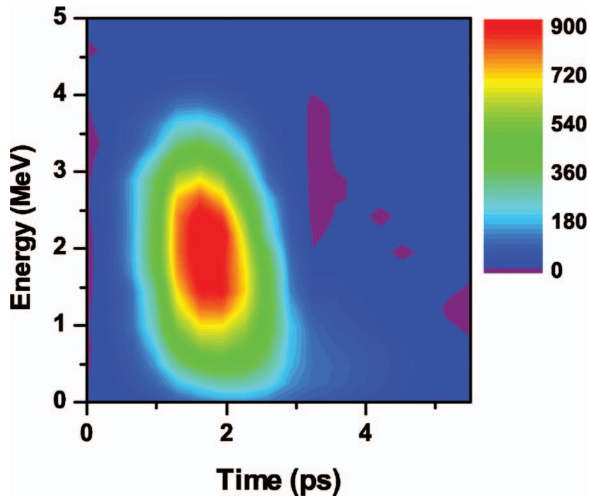

FIG. 4. (Color) Positron spectrum as a function of time, calculated by EGS4 Monte Carlo simulation. The calculation is for the spectrum in Fig. 1(a) with a 1 mm tungsten target. The intensity scale is relative.

In summary, we have proposed a scheme of generating short γ-ray bursts with high average fluxes from a storage ring. While this high flux, short burst of γ-ray may have potential applications in nuclear fluorescence spectroscopy and isotopic imaging, we center our discussion on the potential of generating ultrashort positron bunches using these γ-ray bursts.

This work is supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

[1] *Principles and Applications of Positron and Positronium Chemistry*, edited Y. C. Jean, P. E. Mallon, and D. M. Schrader (World Scientific, New Jersey, 2003).
[2] W. Bauer-Kugelmann, P. Sperr, G. Kögel, and W. Triftshäuser, Mater. Sci. Forum **363–365**, 529 (2001).
[3] Y. Li, Z. Huang, M. D. Borland, and S. Milton, Phys. Rev. ST Accel. Beams **5**, 044701 (2002).
[4] F. V. Hartemann, W. J. Brown, D. J. Gibson, S. G. Anderson, A. M. Tremaine, P. T. Springer, A. J. Wootton, E. P. Hartouni, and C. P. J. Barty, Phys. Rev. ST Accel. Beams **8**, 100702 (2005).
[5] A. Mikhailichenko, Standard Linear Acelerator Center Technical Report No. SLAC-R-0502, 1997 (unpublished), 229.
[6] T. Omori, Y. Takeuchi, and M. Yoshioka, Nucl. Instrum. Methods Phys. Res. A **500**, 232 (2003).
[7] http://www.aps.anl.gov
[8] See, e.g., S. Y. Lee, *Accelerator Physics* (World Scientific, Singapore, 1998), p. 415.
[9] A. A. Zholents and M. S. Zolotorev, Phys. Rev. Lett. **76**, 912 (1996).
[10] K. Holldack, T. Kachel, S. Khan, R. Mitzner, and T. Quast, Phys. Rev. ST Accel. Beams **8**, 040704 (2005).
[11] M. J. Berger, J. H. Hubbell, S. M. Seltzer, J. Chang, J. S. Coursey, R. Sukumar, and D. S. Zucker, XCOM: Photon Cross Sections Database, NIST Standard Reference Database 8 (XGAM), http://physics.nist.gov/PhysRefData/Xcom/Text/XCOM.html
[12] R. Nelson, H. Hirayama, and D. W. Rogers, Standard Linear Accelerator Center Technical Report No. SLAC-265, 1985 (unpublished).
[13] W. Bauer, K. Maier, J. Major, H. E. Schaefer, A. Seeger, H. D. Carstanjen, W. Decker, J. Diehl, and H. Stoll, Appl. Phys. A: Solids Surf. **43**, 261 (1987).