PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **9**, 091001 (2006)

Polarized γ source based on Compton backscattering in a laser cavity

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(Received 24 May 2006; published 27 September 2006)

We propose a novel gamma source suitable for generating a polarized positron beam for the next generation of electron-positron colliders, such as the International Linear Collider (ILC), and the Compact Linear Collider (CLIC). This 30-MeV polarized gamma source is based on Compton scattering inside a picosecond CO_2 laser cavity generated from electron bunches produced by a 4-GeV linac. We identified and experimentally verified the optimum conditions for obtaining at least one gamma photon per electron. After multiplication at several consecutive interaction points, the circularly polarized gamma rays are stopped on a target, thereby creating copious numbers of polarized positrons. We address the practicality of having an intracavity Compton-polarized positron source as the injector for these new colliders.

DOI: 10.1103/PhysRevSTAB.9.091001 PACS numbers: 29.27.Hj, 41.75.Ht, 41.60.Ap, 42.55.Lt

I. INTRODUCTION

Intense beams of circularly polarized gamma rays (γ rays) in the ~30 MeV energy range are required for producing polarized positrons for the next-generation electron-positron (e^--e^+) linear colliders, such as the International Linear Collider (ILC) [1], and the Compact Linear Collider (CLIC) [2]. Two basic schemes of a polarized γ-source are being considered for the ILC: spontaneous radiation of a 150-GeV electron beam (e-beam) in the ~200-meter-long helical wiggler [3,4], and Compton backscattering of a high-intensity laser beam off a 1.3–4 GeV e-beam [5–8].

A polarized positron source (PPS) based on a Compton backscattering is relatively compact, independent from the main linac, and so can offer considerable flexibility, such as easy switching of the positrons' polarization, which is determined by the laser. The same linac that produces the e-beam driving the Compton source can be used as a conventional nonpolarized positron backup source for the ILC. Further, Compton backscattering is the only practical choice for the CLIC due to the degradation of the emittance that occurs in a wiggler.

The concept of a Compton-based PPS (CPPS) has been discussed for several years [5–8]. The evolution of the ILC beam's requirements and laser technologies entailed the corresponding development of this concept. One of the main distinctions between the different CPPS proposals is the wavelength of a laser for the Compton γ-source. The choice typically varies from $\lambda \approx 1\ \mu$m for solid-state lasers (SSL), to $\lambda \approx 10\ \mu$m for CO_2 gas lasers. SSLs are the more conventional devices, widely utilized scientifically; their short wavelength reduces the e-beam energy required for the CPPS. Their high repetition rate of operation and the extremely low optical losses of the typical reflective coatings at $\lambda \approx 1\ \mu$m afford the opportunity for field enhancement in a passive-interferometer accumulating cavity [8]. However, the laser beam and the resulting γ-ray flux lack sufficient energy to avoid having to stack the positron beam in the accumulator ring. Further, a drawback in adopting the interferometer approach is the inevitable deviation from the most efficient geometry for backscattering interactions. The efficiency of 10 μm based Compton source allows one to generate positron bunches without accumulation or stacking.

CO_2 lasers are robust, economical sources of directed radiation. Furthermore, the number of photons per one Joule of laser energy proportionally increases in a throughput of Compton scattering, as was demonstrated at the BNL-ATF where the brightest-ever Compton x-ray source was achieved [9,10] and recently extended into a nonlinear regime [11].

In the present paper, we describe a practical scheme for a polarized γ-source based on commercial CO_2 lasers. Comparing our scheme with earlier CO_2-laser-based CPPS concepts [6], we demonstrate that it better uses laser energy by placing a Compton interaction point (IP) inside an active laser-amplifier cavity [12]. This configuration meets the ILC and CLICs' requirements for the number of captured polarized positrons without needing an accumulation ring, and also opens the way for a higher duty cycle and repetition rate during the collider's operation.

In the following sections, we address the optimization of parameters for the ILC and CLIC to maximize throughput from the PPS. We outline conditions for achieving the most favorable γ-production at the level of one photon per electron at each laser IP, and discuss our experimental tests of this regime at the BNL-ATF. Finally, we describe the architecture of the proposed intracavity polarized γ-source and the steps towards its practical realization for these new e^--e^+ colliders.

II. PARAMETER OPTIMIZATION FOR PPS

Developing a positron injector may be the most challenging task for realizing the next-generation e^--e^+ collider in practice. The ILC designs specify a 3-nC charge per each positron bunch. The expected efficiency of converting polarized γ-photons into polarized positrons is about 2%, optimized for the 60% level of the beam's polarization [6]. Therefore, every positron requires, as precursors, fifty γ-photons assembled in the beam format as the e^--e^+ collider beams. We propose to accumulate this γ-flux via Compton scattering at ten consecutive IPs. In each one, a 4-GeV e-beam, carrying a 5 times higher charge per a bunch (15-nC), undergoes a head-on collision with a CO_2-laser pulse to produce one γ-photon per electron.

The integral efficiency of the γ-production in the collision can be estimated from

$$\frac{N_\gamma}{N_e} = \frac{N_\phi}{S}\sigma_c,$$

where N_γ, N_e, and N_f are the numbers of γ rays, electrons, and laser photons, respectively, S is the cross-sectional area of the interacting beams, $\sigma_c = \frac{8}{3}\pi r_e^2 = 6.652 \times 10^{-29}$ m^2 is the Compton scattering cross section, and $r_e = e^2/mc^2 = 2.818 \times 10^{-15}$ m is the electron's classical radius. For example, for idealized cylindrical beams of 100-μm diameter, the condition $N_\gamma/N_e = 1$ is satisfied at the corresponding energies of the CO_2-laser and the SSL of 2 and 20 J. Further, the SSL requires a 1.3 GeV e-beam to equate with a 4 GeV one for the CO_2-laser; this increases the fraction of the electron energy lost on each scattering event and also the difficulty in maintaining a small e-beam size over a number of IPs due to the bigger geometrical emittance. These considerations point towards our choosing the CO_2 laser as the optimum driver for the CPPS.

We note that estimating the proportion of N_γ/N_e for more realistic Gaussian beams would require transverse and longitudinal integration over the IP space, involving an elaborate mathematical analysis that still might leave questions about the accuracy of a Gaussian approximation for the spatial and temporal distributions in realistically achievable beams. Instead, we offer an experimental verification of reaching the condition $N_\gamma/N_e = 1$, as described next.

Reasonably assuming that the overall cost of the CPPS will be dominated by the e-beam accelerator, it might be desirable to push the laser's power to its practical limits, so attaining maximum N_γ/N_e yields. However, such a trend ultimately might bring us into a regime of nonlinear Compton scattering where multiple laser photons are "absorbed" by an electron, each reemitting a single higher-energy γ-photon. Such Compton harmonics would be radiated at different wavelengths, partially outside the solid cone of the γ-beam wherein the polarized positrons are produced, and so might lower the efficiency of utilization of laser energy, resulting in unproductive consumption of the e-beam's power.

The magnitude of the nonlinear Compton scattering is characterized by the normalized vector potential; $a = e\sqrt{-\langle A_\mu A^\mu \rangle}/mc^2$, where e is the charge of the electron, A_μ is the four-vector potential of the laser, and mc^2 is the electron's rest energy. The parameter a, simply called "laser strength," can be rewritten more conveniently as a function of the laser's wavelength λ and intensity I: $a = 0.60 \times 10^{-9}\lambda[\mu\text{m}]I^{1/2}[\text{W/cm}^2]$. The nonlinear Compton scattering approaches the linear process at $a \geq 1$, thereby putting an upper limit on the laser's best intensity for the CPPS.

To complete optimizing the laser's parameters, such as the peak power P, pulse duration τ, and the energy per pulse E, we note that to maintain the maximum efficiency of the laser and e-beam interactions, the laser's focal spot should match the e-beam's size, and its pulse length should be close to the Rayleigh length $R_L = \pi w_o^2/\lambda$, where w_o is the laser beam's radius at the focal plane. For a Gaussian beam with an FWHM diameter of 100 μm, $w_o = 70$ μm. Then, $R_L \approx 1.5$ mm, the corresponding optimum pulse length of the CO_2 laser is $\tau = 5$ ps, and the limiting condition $a = 1$ is attained at $P = 1$ TW and $E = 5$ J.

As discussed, a high-charge e-beam driving a Compton source should be constrained to a low angular divergence throughout the laser's interaction region. Divergence of electrons reduces the γ-yield, smearing the Compton backscattering energy's dependence upon the emission angle, and so degrading the positron beam's polarization. We propose to generate a train of low-emittance drive electron bunches using a rf photoinjector gun and accelerate them to 4 GeV energy with a linear accelerator. The selected interval between bunches in the Compton drive e-beam will correspond to the linac's optimum loaded gradient. We consider a 3-m-long SLAC-type accelerator module providing the total acceleration

$$\Delta E[\text{MeV}] = 10.8 \times \sqrt{P_{\text{rf}}[\text{MW}]} - 39.5 \times I[\text{A}],$$

where P_{rf} is a klystron power, and I is an equivalent steady-state current. A 80-MW klystron would produce a 16 MV/m acceleration gradient for the 30-nC bunch charge and a 12-ns bunch spacing suitable for the Compton drive linac. Accordingly, a linac approximately 250-m long would be required to generate the 4 GeV e-beam to drive the CPPS.

The normalized emittance of such an e-beam is expected to be ~5–10 μm for the 15-nC bunches [13–15]. Its focusing system would need to generate one with a beta function of 1 m at the waist that would entail beam sizes of root-mean-square (rms) width $\sigma = 25 \div 35$ μm in the middle, and $35 \div 50$ μm at the ends of the entire ~2 meter-long interaction region that extends over ten IPs. The divergence from a 4-GeV e-beam will be 5 times smaller than $1/\gamma$, and, therefore, will not lower the achievable polarization level. Simultaneously, a CO_2-laser spot size with $2\sigma_L \equiv w_o = 70$ μm can be realized as was demonstrated experimentally [9]. Evidently, a 1.3 GeV

TABLE I. CO_2 laser- and e-beam parameters at the Compton IP.

Normalized vector potential	a_0	0.5
Laser focus size	w_0	70 μm
Rayleigh length	R_L	1.5 mm
Laser beam length	τ_L	5 ps
Laser beam energy	E_L	2 J
Electron beam size	σ	25–35 μm
γ-ray production efficiency	$N_\gamma N_\varepsilon$	$\sim$1

e-beam will be correspondingly $\sim\sqrt{3}$ times wider and will not fit into the tightly focused laser beam.

Summarizing this discussion on optimizing the IP for the Compton γ-source, we propose the set of parameters compiled in Table I.

The format of the laser pulse should match the collider's design matrix. The basic ILC design calls for trains of 2820 pulses at intervals of 300 ns, with a 5 Hz train repetition rate. Such a format is not optimal for pulsed CO_2 lasers or for high-average-current linacs. Instead, we suggest generating 100 bunches spaced by 12 ns to form a 1.2-μs-long train with a repetition rate of 150 Hz, thus maintaining the total number of bunches per second the same as in the original ILC design. By firing the linac and laser system 30 times, 3000 positron bunches can be created and stored in the ILC dumping ring, so forming an injection beam. This format is also beneficial for the operation of the capture linac section that is a very challenging item in every other approach.

The operation mode is simplified for the CLIC where only 100 positron-bunches are needed with about $1/10$ of the ILC's charge in each one. Hence, the Compton drive-beam's charge could be reduced, and intrabunch spacing shortened. A dumping ring will not be needed for building up a positron beam; the correct beam structure would be produced directly from the Compton interactions. Intrabeam intervals would be adjusted to the CLIC's requirements in the dumping or predumping rings. The CLIC's repetition rate is 150 Hz that naturally matches the drive linac and a laser system.

III. EXPERIMENTAL TEST OF X-RAY YIELD IN COMPTON SCATTERING

The experiment reported here is a continuation of BNL-ATF's systematic approach over the past several years to optimizing the Thomson scattering process towards maximum photon yield [9–11]. We use the backscattering (180°) between the laser and electron beams as the most efficient interaction geometry.

The BNL-ATF is the only facility in the world equipped for testing the Compton scattering process close to these optimum conditions outlined above. The main equipment for the test includes a 5-ps CO_2 laser and a 60-MeV high-brightness photocathode rf electron linac. A relatively low e-beam energy does not change the underlying physics of the Compton interaction, but merely shifts the scattered photons into the soft x-ray region of 6.5 keV. We note that, as long as the produced photon's energy is much less than that of the electron's energy, i.e., $h\nu \ll \gamma m_e c^2$, it is more appropriate to refer to this process as Thomson scattering rather than Compton scattering.

Figure 1 is a principle diagram of the present experiment. The typical input parameters for the electron- and CO_2-laser beams are as follows: Electron beam: energy 60 MeV, bunch charge 0.2 nC, duration 3.5 ps (FWHM), transverse dimensions at the interaction point $45 \times 80\ \mu m^2$ (rms); laser pulse: energy 2 J, duration 5 ps (FWHM), and, focal spot size 35 μm (rms). The laser pulse, introduced into the e-beam line through a potassium-chloride salt (KCl) window, is reflected along the e-beam's direction by a flat copper (Cu) mirror tilted at a 45° angle, and is focused head-on to the e-beam with a normal-incidence parabolic mirror with a ratio of equivalent focal length to the diameter f/#=1. Both mirrors have 2-mm central holes drilled along the e-beam's axis to transmit it and the generated x rays.

A narrow cone of x rays with the angular divergence $\theta = 1/\gamma$ or $\sim$8 mrad radiated from the interaction area passes through the hole in the parabolic mirror and is extracted from the e-beam line through a 250 μm thick beryllium (Be) vacuum window. Spent electrons, deflected by a 90°

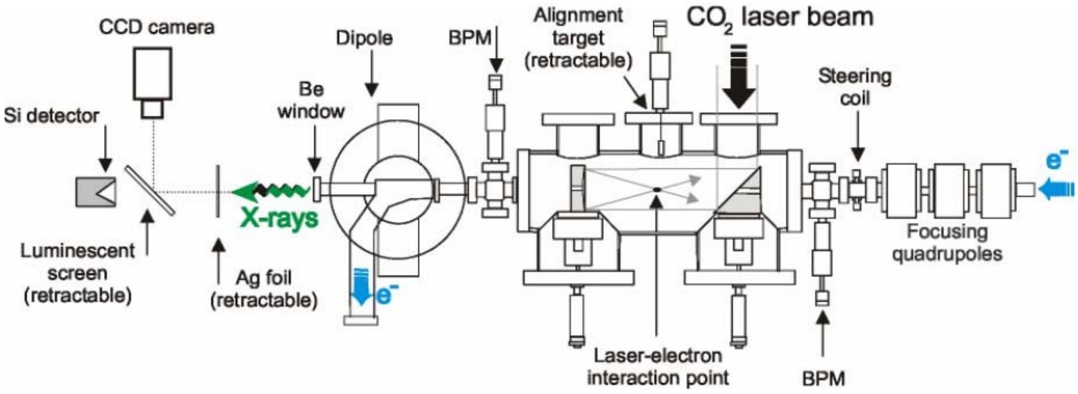

FIG. 1. (Color) Principle diagram of the BNL-ATF Thomson scattering experiment.

dipole magnet, do not reach the Be window, so minimizing parasitic bremsstrahlung noise on the x-ray detectors positioned behind it. To image the transverse intensity profile of the x-ray beam, we used a luminescent screen (Kodak-2854) viewed with a CCD camera.

Alternatively, we employed a wide-aperture silicon (Si) diode to measure the integral x-ray yield. The amplitude of the signal measured by the Si detector was normalized to the integral x-ray pulse energy produced in the IP using independent detector calibration with a standard x-ray source, taking into account the spectral transmission of the Be window and the air gap between it and the detector. From these measurements, we estimated that the total number of Thomson x rays produced at the IP was 3×10^8.

Inserting a 10 μm thick Ag foil in front of the detector excluded the low-energy x rays produced in the linear (single-photon) process. After filtering by the Ag foil, the signal on the Si detector dropped 12 fold. Simultaneously, we could visualize the nonlinear component in Thomson scattering on a luminescent screen.

To verify the experimental results, we undertook Monte Carlo simulations using the computer code CAIN [16] based on the Volkov solutions to the Dirac equation. This code calculates radiation scattering from electrons assuming Gaussian temporal and spatial distributions of the focused electron and laser beams. The following beam parameters were simulated: e-beam—size 60 μm (rms), charge 0.2 nC, duration 3.5 ps (FWHM); laser—energy 2 J, size 35 μm (rms), duration 5 ps (FWHM). Table II has the results of these simulations. The simulated x-ray yields fully agree with our experimental observations.

The simulations indicate that the proportion of the x-ray energy "wasted" into harmonics does not exceed 15%. The x-ray flux filtered by the 10-μm Ag foil consists primarily of harmonics, as confirmed in our experiment wherein we observed a distinctive transformation of the angular distribution of the x rays on a luminescent screen with and without the Ag filter. The x-ray distribution changed from a narrow peak centered on the e-beam's axis into a distinctive double-lobe structure typical of the second harmonic of Thomson scattering produced with a linear polarized laser [11]. Similarly, we observed a ring-structured angular distribution for a circular polarized beam. We note that changing between linear- and circular-polarization did not affect the absolute amplitude of the integral x-ray signal, or the contribution of the nonlinear component.

TABLE II. CAIN simulation results for the BNL-ATF's experiment conditions.

Parameter	Total	Harmonics
Number of x-ray photons at IP	3×10^8	1.6×10^7
Integral x-ray energy at IP (eV)	10^{12}	1.5×10^{11}
Number of x-ray photons at detector	0.7×10^8	1.5×10^7
Energy on detector (eV)	4×10^{11}	4×10^{10}
Filtered energy on detector (eV)	3.1×10^{10}	3.0×10^{10}

A 0.2 nC electron bunch contains 1.25×10^9 electrons, i.e., 4 times the number of photons generated at IP (see Table II). However, because the cross section of the e-beam is approximately double that of the laser's focus, only $\sim\frac{1}{4}$ of the total electrons in the bunch were scattered. Thus, we conclude that average scattering rate for the electrons within the counterpropagating laser pulse is close to $N_\gamma/N_e = 1$, as is required for the CPPS.

IV. CO$_2$ LASER SYSTEM FOR CPPS

Finally, we describe architecture of a cascaded laser system designed for the proposed PPS for the ILC and CLIC based on the intracavity Compton scattering between the counterpropagating 4-GeV electron and CO$_2$ laser beams. This cascade is designed to deliver polarized CO$_2$ laser beams circulating inside ten so-called Compton cavities, with the round-trip time being the exact integer of the 12-ns space between the bunches. As shown in Fig. 2, it consists of two prime subassemblies: a pulse feeder, and regenerative Compton cavities. The feeder generates pairs of identical 1–2 J, 5-ps laser pulses spaced by 12-ns at a 150 Hz repetition rate. They are injected into individual regenerative amplifiers for each sequential laser/e-beam IP, wherein the laser pulse train circulating for 1.2 μs participates in 100 interactions. Each laser beam will be focused at one of the ten IPs in a spot size of $\sigma_L \approx 35$ μm.

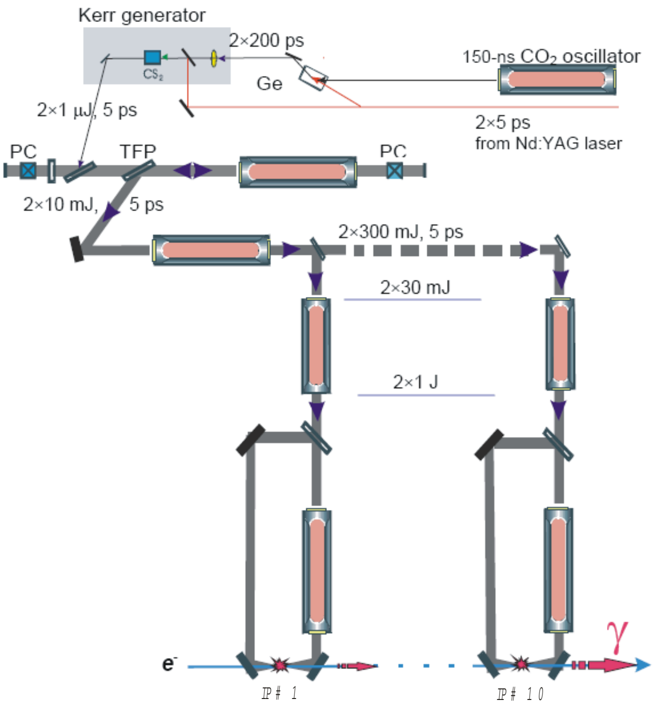

FIG. 2. (Color) Proposed layout of a polarized gamma source based on Compton scattering inside resonator cavities in a series of CO$_2$ laser amplifiers. PC stands for Pockels cell, TFP—thin film polarizer.

To produce such laser beams, we start by slicing a pair of picosecond pulses typically from a 150-ns CO_2 laser oscillator pulse. This operation can be done at BNL's ATF using the similarly formatted Nd:YAG laser pulses and the optical switching techniques, such as semiconductor optical switching [17] and a Kerr switch [18].

The CO_2 laser pulses then are seeded and trapped inside a regenerative amplifier cavity with a round-trip time in an exact multiple of the spacing inside the train (e.g., $12 \times 2 = 24$ ns). About ten passes amplify the energy 10 000 times. The amplified pulses are dumped from the regenerative cavity with a Pockels cell and, after further amplification to 1–2 J/pulse, are split with partial reflectors in ten beams and injected into individual regenerative ring cavities, one for each IP. Intracavity "simmer" amplifiers compensate just for the optical losses during the 1.2 μs interval needed for the lasers' multiple interactions with 100 electron bunches. The entire laser system operates at the electron macro-bunch repetition rate (150 Hz).

The Compton IP inside the regenerative-amplifier ring cavity is positioned at the joint focal point of two confocal parabolic mirrors with an axial hole drilled to transmit e-beam and γ rays, similar to the arrangement in the earlier BNL-ATF experiment [10]. It ensures the most efficient backward scattering where the paths of the laser and electron beams exactly overlap.

Note that a high-pressure gas laser technology is crucial for operating CO_2 laser amplifiers in the picosecond regime, providing sufficient spectral bandwidth via overlapping rotational molecular spectral lines pressure broadened at about 10 atm. The BNL-ATF's high-pressure CO_2 laser system already delivers 5-J, 5-ps pulses but in a slow repetition rate regime (1 shot in 20 s) [19].

Bringing a high-pressure laser system to a higher repetition rate is within the capabilities of contemporary technology. One such commercial laser, WH-20 manufactured by Scientific Development and Integration Ltd., SDI (Pretoria, Republic of South Africa), is employed in BNL's laser system as a multipass regenerative 5-ps amplifier. This 10-atm CO_2 laser operates at a 10 Hz repetition rate. A more powerful model WH-500 can be modified to operate at a 150 Hz repetition rate with average power 0.75 kW. These parameters are sufficient for any stage in the cascaded CO_2 laser system described above including the most challenging final amplifier that serves to reimburse optical losses of 1-J laser pulses circulating inside a Compton cavity that are estimated to $\sim$5% per a round-trip. This is confirmed by simulations based on solving Maxwell-Bloch equations [20] and can be illustrated by the following simple estimates.

Under strong saturation, the 1-J laser pulse will extract $\sim$30% of the stored energy defined by $g_0 \times W_s \times V_a$ in a single pass, where $g_0 = 0.4\%/\text{cm}$ is a small-signal gain, $W_s \approx 400\ \text{mJ/cm}^2$ is a saturation flux, and $V_a = 50\ \text{cm} \times 2\ \text{cm}^2 = 100\ \text{cm}^3$ is a typical dimension of an active medium of a commercial high-pressure amplifier. The resulting 50 mJ energy extraction in each pass is sufficient for replenishing the 5% round-trip optical losses in the Compton cavity. A 12-ns period between the pulses circulating inside the Compton cavity allows complete recovery of the population inversion to the original level through pumping and relaxation processes. The total time interval of 1.2 μs necessary for laser interaction with 100 electron bunches is a typical gain lifetime for a high-pressure CO_2 laser. Calculating average power delivered by the laser gives $50\ \text{mJ} \times 100\ \text{pulses} \times 150\ \text{Hz} = 0.75\ \text{kW}$ that is achievable with the present-day gas-laser technology.

V. CONCLUSIONS

We propose a polarized γ-ray source based on commercial laser and accelerator technologies. To accumulate the high number of 30-MeV γ-photons required for the ILC PPS, we will use backscattering from a 4-GeV e-beam inside a CO_2-laser regenerative amplifier and repeat this process at ten consecutive IPs.

Implementing such interaction geometry is impossible in previously proposed CPPS configurations [8]. First, unlike the linac used in the present proposal, the suggested synchrotron accelerator cannot tightly focus the e-beam, so that the laser/e-beams' overlap is reduced, as is the efficiency of gamma production, resulting in extra divergence of the γ-beam. In addition, a bigger hole is needed in the mirrors, so causing extra losses from the laser beam.

Second, a compact configuration with short focal-length parabolic mirrors would not be well suited to the suggested SSL. For the same focal spot size, the SSL has a $\sim$10 times smaller angular divergence than a CO_2 laser. Consequently, the laser's size on a mirror would be too small (incurring problems of optical damage and extra losses when a compact laser beam impinged on a hole in the mirror), or the mirrors would need to be moved further apart, an approach that conflicts with a higher angular divergence of γ rays produced from a 1.3-GeV e-beam as opposed to 4-GeV in the case of a CO_2 laser.

Finally, the proposal for including a high-finesse interferometric cavity for enhancing the SSL's field [8] rules out using relatively lossy mirrors with a hole. Consequently, the needed several degree tilt between the axes of the e-beam and SSL beam would reduce the efficiency of their interaction compared with a pure backscattering geometry implemented in the present proposal.

This comparison confirms that all the major elements of the present proposal, such as a CO_2 laser instead of the SSL, a linac instead of a synchrotron, and backward scattering through holes in focusing mirrors in place of an interferometric pulse-stacking cavity, are intricately linked together to afford a practical solution for CPPS.

BNL's AFT demonstrated the production of the required CO_2 laser beam, as well as high-efficiency Compton backscattering that meets the ILC PPS requirements. Further, the source we propose considerably exceeds the requirements for the CLIC. Research and development is needed, however, to verify the laser's "intracavity" interaction mode at a high repetition rate.

ACKNOWLEDGMENTS

We thank D. Cline, V. Litvinenko, T. Kumita, and other colleagues who contributed to initiating this study. This study is supported by the U.S. Department of Energy under Contract No. DE-AC02-98CH10886 and Japan/U.S. cooperation in the field of High Energy Physics.

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