EXPERIMENTAL DEMONSTRATION OF FEASIBILITY OF A POLARIZED GAMMA-SOURCE FOR ILC BASED ON COMPTON BACKSCATTERING INSIDE A CO_2 LASER CAVITY*

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Abstract

Compton interaction point incorporated into a laser cavity is the key element of the Polarized Positron Source (PPS) concept proposed for ILC in [1]. According to this proposal, circularly polarized gamma rays are produced via Compton backscattering from a linac's electron beam (e^--beam) inside a CO_2 laser amplifier cavity. Intra-cavity positioning of the interaction point (IP) allows laser energy recycling to match the electron beam format. We conducted experimental tests of multi-pulse operation of such active Compton cavity upon injection of a picosecond CO_2 laser beam. Together with earlier demonstration of a high x-ray yield via the e^--beam/CO_2-laser backscattering, these new results show a viability of the entire PPS concept and closely prototype the laser source requirements for ILC.

INTRODUCTION

Intense beams of circularly polarized gamma rays (γ-rays) in the 30-40 MeV energy range are required for producing polarized positrons for the next-generation electron-positron (e^--e^+) linear colliders, such as the ILC [2] and the Compact Linear Collider (CLIC) [3]. Two basic schemes of a polarized γ-source presently are being considered for the ILC: spontaneous radiation of a 150-GeV e^--beam in the ~200-meter-long helical wiggler, and Compton backscattering of a laser beam off a 1.3-4 GeV e^--beam [4,5]. A PPS based on a Compton backscattering avoids emittance degradation that occurs in a wiggler, is independent from the ILC 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 to drive the Compton source can be used as a conventional non-polarized positron backup source for the ILC.

The wavelength of a laser is one of the main distinctions between the different Compton PPS proposals. The choice typically varies from $\lambda \approx 1$ μm for solid-state lasers (SSL) [5], to $\lambda \approx 10$ μm for CO_2 gas-lasers [4]. In addition to being robust and economical sources of directed radiation, CO_2 lasers deliver ten times bigger number of photons per one Joule of laser energy that proportionally increases in a throughput of Compton scattering. This was demonstrated at the BNL-ATF where the brightest-ever Compton x-ray source was achieved [6] and recently extended into a nonlinear regime [7]. Placing the Compton IP inside an active laser-amplifier cavity considerably improves utilization of the laser output and allows to meet the requirements of the ILC and CLIC for the number of produced polarized positrons.

In the present paper we describe a practical scheme for a polarized γ-source based on commercial CO_2 lasers. We describe the architecture of the proposed intra-cavity polarized γ-source for the ILC and CLIC, and outline conditions for achieving an optimum γ-production at the level of one photon per electron at each laser IP. We discuss our experimental tests of this regime together with demonstration of the multi-pulse operation of the laser amplifier that incorporates intra-cavity Compton IP.

PARAMETER OPTIMIZATION

Developing a positron injector may be the most challenging task for practically realizing the next-generation e^--e^+ collider. The ILC and CLIC designs specify a 1 nC charge per each positron bunch. The conversion efficiency of the polarized γ-photons into polarized positrons is expected to be about 2%. Therefore, every positron requires, as precursors, fifty γ-photons assembled in the same format (bunch length and repetition rate) as the e^--e^+ collider beams.

The integral efficiency of the γ-production in the head-on collision can be estimated from $\frac{N_\gamma}{N_e} = \frac{N_\phi}{S}\sigma_c$, where N_γ, N_e, and N_ϕ are the numbers of γ-rays, electrons, and laser photons, S is the cross-section area of the interacting beams and $\sigma_c = 6.652\times10^{-29}\,m^2$ is the Compton cross-section.

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 the electron, each re-emitting a single higher-energy γ-photon outside the solid cone of the γ-beam wherein the polarized positrons are produced. This might lower the efficiency of utilization of laser- and e^--beam energy. An intuitive conclusion that one scattered laser photon averaged per each electron is a border-line between the linear and nonlinear scattering regimes has been verified experimentally [1]. For idealized cylindrical beams of 100 μm diameter, the condition N_γ/N_e=1 is satisfied at the corresponding CO_2-laser or SSL energy of 2 J and 20 J, thereby putting the requirement on the optimum laser intensity for the Compton PPS. Furthermore, the SSL requires a 1.3 GeV e^--beam to equate with a 4 GeV one for CO_2. This increases the fraction of the electron energy lost on each scattering event, and the difficulty in maintaining a small e^--beam

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size over a number of IPs due to a bigger geometrical emittance. These considerations further support our choice of the CO_2 laser as an optimum driver for the Compton PPS.

To complete the optimization of the laser's parameters, let us note that, for maintaining 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 a FWHM diameter of 100 μm, w_O=70 μm. Then, $R_L \approx 1.5$ mm, and the optimum pulse length of the CO_2 laser turns out to be $\tau =$ 5 ps.

With N_γ/N_e=1, and 10 nC/bunch delivered from the electron linac, five consecutive Compton IPs will be required to accumulate the γ-flux for the 1-nC positron bunch production. The design parameters for the Compton PPS compiled in Table 1 meet the ILC and CLIC requirements on the average positron current.

Table 1: Requirements to the Compton PPS based on using a CO_2 laser and the 4-GeV electron linac.

Parameter	**Symbol**	**Value**
Pulse repetition rate	f_{rep}	150 Hz
Bunches per pulse	N_b	100
Bunch Spacing	Δt	12 ns
Laser energy	E_{laser}	1 J
Size at focus	σ_{laser}	40 μm
Laser pulse length	τ_{laser}	5 ps
Number of γ per electron	N_γ/N_e	1
Number of e^- per bunch	N_e	6×10^{11}
Number of lasers	N_{laser}	5
Number of γ per bunch	$N_\gamma \times N_{laser}$	3×10^{12}

In the following paragraphs we describe the design of the laser system that provides the desirable pulse format and review our recent demonstrations of the required number of γ–photons per electron and the number of laser pulses that pass the Compton IP per every laser shot.

CO_2 LASER FOR COMPTON PPS

The architecture of a cascaded laser system based on the intra-cavity Compton scattering between the counter-propagating 4-GeV electron- and CO_2 laser beams is shown in Fig.1. It consists of two prime subassemblies: a pulse feeder, and regenerative Compton cavities. A feeder generates pairs of identical 1 J, 5-ps laser pulses spaced by 12 ns at a 150 Hz repetition rate. The pulses 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.

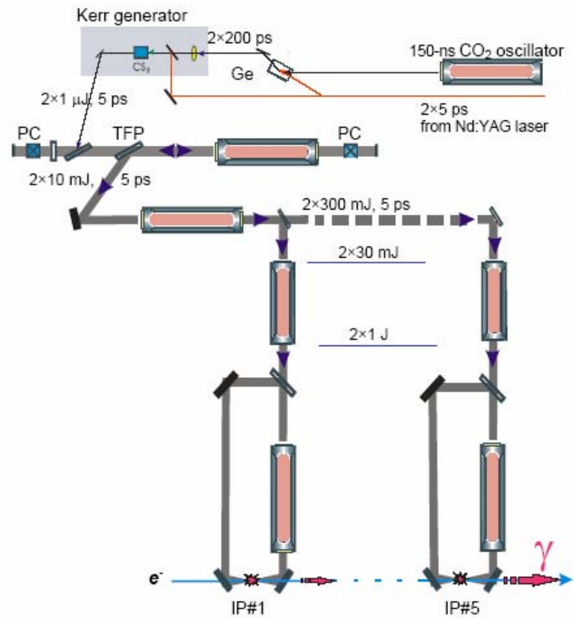

Figure 1: Layout of a laser system designed for the proposed PPS for the ILC and CLIC.

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

The produced CO_2 laser pulses are seeded and trapped inside a regenerative amplifier cavity. Multiple passes (~10) are required to amplify the energy 10,000 times. The amplified pulses are extracted from the regenerative cavity with a Pockels cell and, after further amplification, split with partial reflectors in five beams. After amplifying these laser beams to 1-2 J/pulse, they are injected into individual regenerative ring-cavities, one for each IP. A round-trip time inside each cavity is the exact multiple of the spacing inside the electron bunch train (e.g., 12×2=24 ns). Intra-cavity "simmer" amplifiers serve to compensate 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). Each laser beam will be focused at one of the five Compton IPs in a spot size of $\sigma \approx 35$ μm at the joint focal point of two confocal parabolic mirrors with an axial hole drilled to transmit e^--beam and γ-rays. This ensures the most efficient backward scattering where the laser and electron paths exactly overlap.

We note that high-pressure gas-laser technology is crucial for operating a CO_2 laser in the picosecond regime, providing sufficient spectral bandwidth in overlapping rotational molecular spectral lines pressure-broadened at about 10 atm. An example is the model WH-500 from SDI Ltd. (Pretoria, Rep. of S. Africa). This laser operates at a 150 Hz repetition rate with average power

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0.5 kW. These parameters are sufficient for any stage in the cascaded CO_2 laser system described above.

PROOF-OF-PRINCIPLE EXPERIMENTS

The BNL-ATF is the only facility in the world equipped for testing the Compton scattering process close to the optimum conditions outlined above. The 1-TW, 5-ps CO_2 laser system and a 60-MeV high-brightness photocathode RF electron-linac operated at the BNL-ATF have been used for testing the most crucial elements of the proposal. In particular, we were able to demonstrate the N_γ/N_e=1 photon production in Compton backscattering and circulation of a long train of picosecond pulses inside the CO_2 laser amplifier ring cavity configured to accommodate the Compton IP.

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. 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 Cu mirror tilted at a 45^o 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 electrons and the generated x-rays. 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 psec (FWHM), cross-section at the interaction point 45×80 μm^2 (RMS); laser pulse: energy 2 J, duration 5 ps (FWHM), and, focal spot size 35 μm (RMS). The number of photons generated at IP under these conditions was equal to the total number of electrons that passed the laser focus (N_γ/N_e=1). Simultaneously, the proportion of the x-ray energy "wasted' into harmonics does not exceed 15% [1].

To check the possibility of recycling the laser pulse by placing the Compton IP inside the CO_2 laser amplifier, we used the same picosecond laser system as in the reported Compton scattering experiment. A pair of confocal parabolic mirrors with the axial hole intended for the e^--beam and γ-ray transmission has been assembled as a part of the CO_2 regenerative amplifier ring cavity. A picosecond, linearly polarized CO_2 laser seed pulse produced by the front end of the BNL-ATF laser system has been injected into the cavity through a hole in the parabolic mirror. By proper balancing gain and losses in the amplifier, we achieved the regime of a steady grow of the seed pulse to the stationary level maintained at the amplitude accuracy of ±3% over 1 μs time interval (see Fig.2). This confirms the possibility of establishing a stable resonator mode in this unconventionally configured laser cavity.

CONCLUSIONS

We initiated R&D on a novel polarized γ-source based on Compton backscattering inside a CO_2 laser cavity that affords a practical solution for ILC PPS. BNL's ATF works towards demonstration of the required CO_2 laser beam format, as well as high-efficiency Compton backscattering. Optical slicing of 5-ps CO_2 pulses has been demonstrated and up to 5-J pulses are used in experiments. laser/e^--beam interaction conditions are optimized and a record-high x-ray yield has been achieved. Production of one x-ray photon per every electron was demonstrated. Nonlinear scattering is observed. Compton IP is incorporated into the laser amplifier cavity and a stable pulse train through the IP has been demonstrated. Picosecond CO_2 lasers with up to 500 Hz repetition rate are commercially available. A CO_2 laser system for ILC polarized γ-source based on intra-cavity Compton backscattering is within a reach.

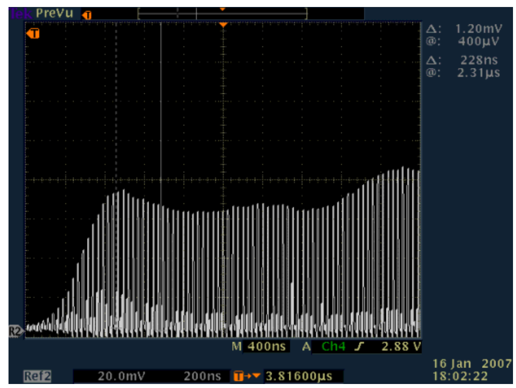

Figure 2: Pulse train inside a ring laser cavity that incorporates the Compton IP as is shown in Fig.1.

REFERENCES

[1] V. Yakimenko and I. V. Pogorelsky, Phys. Rev. ST Accel. Beams 9 (2006) 091001.

[2] The Linear Collider Physics Resource Book for Snowmass 2001, pp. 333-345; http://www.slac.stanford.edu/grp/th/LCBook/positron.pdf.

[3] CERN Report 2004-005: Physics at the CLIC Multi-TeV Linear Collider, editors; M. Battaglia, A. de Roeck, J. R. Ellis, and D. Schulte, p. 208; ISBN: 92-9083-226-6 http://cdsweb.cern.ch/search.py?recid =749219&ln=en.

[4] T. Hirose, K. Dobashi, Y. Kurihara, T. Muto, T. Omori, T. Okugi, I. Sakai, J. Urakawa, and M. Washio, NIM A455 (2000) 15.

[5] T. Omori, M. Fukuda, T. Hirose, Y. Kurihara, R. Kuroda, M. Nomura, A. Ohashi, T. Okugi, K. Sakaue, T. Saito, J. Urakawa, M. Washio, and I. Yamazaki, Phys. Rev. Lett. 96 (2006) 114801.

[6] I.V. Pogorelsky, I. Ben-Zvi, T. Hirose, S. Kashiwagi, V. Yakimenko, K. Kusche, P. Siddons , J. Skaritka, T. Kumita, A. Tsunemi, T. Omori, J. Urakawa, M.Washio, K. Yokoya, T. Okugi, Y. Liu, P. He, and D. Cline, Phys. Rev. ST Accel. Beams 3 (2000) 090702.

[7] M. Babzien, I. Ben-Zvi, K. Kusche, I. V. Pavlishin, I. V. Pogorelsky, D. P. Siddons, .V. Yakimenko, D. Cline, F. Zhou, T. Hirose, Y. Kamiya, T. Kumita, T. Omori, J. Urakawa, and K. Yokoya, Phys. Rev. Lett. 96 (2006) 054802.

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