Polarimetry of Short-Pulse Gamma Rays Produced through Inverse Compton Scattering of Circularly Polarized Laser Beams

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We have developed a polarimetry of ultrashort pulse γ rays based on the fact that γ rays penetrating in the forward direction through a magnetized iron carry information on the helicity of the original γ rays. Polarized, short-pulse γ rays of $(1.1 \pm 0.2) \times 10^6$/bunch with a time duration of 31 ps and a maximum energy of 55.9 MeV were produced via Compton scattering of a circularly polarized laser beam of 532 nm off an electron beam of 1.28 GeV. The first demonstration of asymmetry measurements of short-pulse γ rays was conducted using longitudinally magnetized iron of 15 cm length. It is found that the γ-ray intensity is in good agreement with the simulated value of 1.0×10^6. Varying the degree of laser polarization, the asymmetry for 100% laser polarization was derived to be (1.29 ± 0.12)%, which is also consistent with the expected value of 1.3%.

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Introduction.—It is widely accepted that polarized positron beams at future electron-positron linear colliders will play a significant role in studying the details of the standard model as well as discovering phenomena beyond the standard model. In 1996, we proposed a new method for creating highly polarized positrons [1] based on two fundamental processes: i.e., inverse Compton scattering of circularly polarized laser photons and successive pair creation from longitudinally polarized γ rays. Here, the helicity of a laser photon is either $+1$ (right-handed, R) or -1 (left-handed, L) [2]. Figure 1 shows the differential cross section of the Compton scattering of a right-handedly polarized laser photon with a wavelength of 532 nm on an unpolarized 1.28-GeV electron. Note that γ rays with a helicity of -1 are highly polarized in the energy region close to the maximum energy, i.e., 56 MeV.

In order to verify the proposed scheme as well as to accumulate technical information on various processes involved in the proposed scheme, we have pursued experimental studies using electron accelerators and laser systems [3–5] as well as a conceptual design of the polarized positron source of the Global Linear Collider (GLC) [6,7]. The important step of a proof-of-principle study is to establish polarimetry for short-bunch γ rays and positrons whose time duration is a few tens ps. The γ-ray polarization can be determined through spin-dependent Compton scattering of γ rays on $3d$ electrons in a magnetized iron (called a magnet hereafter). As shown in Fig. 2, the cross sections of the Compton process are given separately for the cases that the γ-ray spin and the electron spin are parallel and antiparallel to each other. As seen in Fig. 2, the electron and the positron pair creation causes a considerably large background, which becomes a serious obstacle to a polarization measurement. Thus, in order to avoid the background, we ordinarily have to select only the Compton process by means of a coincidence method. Unfortunately, such a short-bunch width of the γ-ray beam prevents us from identifying both the electron and γ photon emerging from a single Compton process.

It was reported in Refs. [8–10] that the circular polarizations of γ rays were studied by measuring the Compton transmission of γ rays through a magnetized iron. This method, called a transmission method, can be applicable to polarization measurements of γ rays with any time structure, and is influenced only a little by the background arising from the pair creation, because transmitting γ rays are collimated to a narrow forward cone while the Compton scattering and pair creation emit, respectively, γ rays and e^--e^+ pairs over wide angular regions.

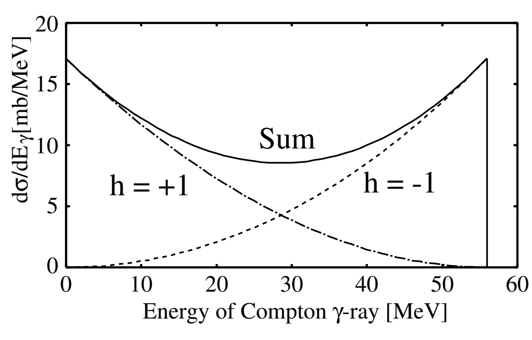

FIG. 1. Differential cross section of the Compton scattering of a laser photon with a wavelength of 532 nm on a 1.28-GeV electron as a function of the γ-ray energy. The dashed and dash-dotted curves correspond to helicities of $+1$ and -1 for the γ ray, respectively. Here the laser light is right-handedly polarized.

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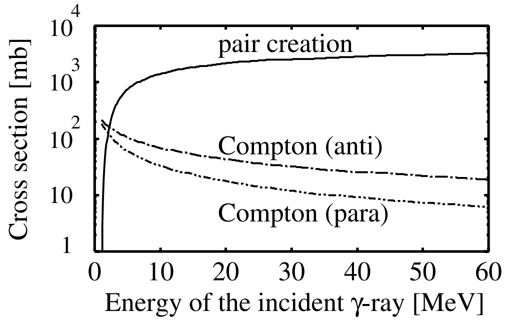

FIG. 2. Total cross section of pair creation and Compton scattering for the cases in which the spin of a γ ray are parallel and antiparallel to that of an electron. In the pair-creation process, the screening is considered.

TABLE I. Parameters of the e^- and laser beams. $\sigma_{x,y}$, beam size at the collision point; $\epsilon_{x,y}$, emittance; $\beta_{x,y}$, beta function; $\frac{\sigma_p}{p}$, momentum spread.

	Electron beam	Laser beam
Energy	1.28 GeV	2.33 eV (532 nm)
Intensity	0.65×10^{10} e^-/bunch	400 mJ/pulse
Bunch length (rms)	31 ps	3.6 ns
σ_x	87 μm	154 μm
σ_y	72 μm	151 μm
ϵ_x	1.94×10^{-9} rad m	11.5×10^{-8} rad m
ϵ_y	2.36×10^{-11} rad m	12.9×10^{-8} rad m
β_x	0.513 m	0.104 m
β_y	52.859 m	0.058 m
Rep. rate	3.12 Hz	1.56 Hz
$\frac{\sigma_p}{p}$	8.2×10^{-4}	⋯

We therefore adopted a method in which we measured at a downstream position of the magnet only the intensity of transmitting γ rays, $N_{\uparrow\uparrow}$ and $N_{\uparrow\downarrow}$, for the parallel and antiparallel cases, respectively. This allowed us to determine the asymmetry, defined as $A = (N_{\uparrow\uparrow} - N_{\uparrow\downarrow})/(N_{\uparrow\uparrow} + N_{\uparrow\downarrow})$. This Letter addresses a detailed study of the γ-ray polarimeter based on an extensive Monte Carlo simulation and presents the first demonstration of a polarization measurement of short-bunch γ rays by means of the transmission method.

Polarized γ-ray production.—A series of experiments has been conducted at the KEK-ATF (Accelerator Test Facility) [11], which consists of an *S*-band linac, a damping ring, and an extraction line. Table I puts together the parameters of the electron beam extracted from the damping ring and the laser beam provided with a *Q*-switch Nd:YAG laser. The laser light is converted into circularly polarized light while passing through the quarter-wave plate. Generated γ-ray beams, which are longitudinally polarized, have a maximum energy of 56 MeV and a time duration of 31 ps, which, being the same as that of electron beams, is considerably shorter than the laser beam one of 3.6 ns in rms. It is remarked that γ rays are highly collimated and that 97% of all γ rays are included within a scattered angle of 3 mrad: This characteristic is beneficial to the design of a transmission-type polarimeter.

Figure 3 shows an apparatus called a Compton chamber, in which laser-electron collisions take place, together with the laser-beam optics and the elements of the polarimeter, i.e., the photodiode, aerogel Cherenkov counter, magnet, and air Cherenkov counter. In order to accomplish precise diagnostics for both the electron and laser beams, we installed screen monitors, a wire scanner, and a knife-edge scanner in the cells of the Compton chamber, as described below (see Fig. 3). The screen monitors were mounted in the central cell located at the collision point and in the side cells placed at a distance of 265 mm from the collision point, so as to adjust the transverse position and the angle of both beams. Furthermore, the wire scanner and the knife-edge scanner are set in the central cell; the former allows one to measure the electron-beam size at the collision point with an accuracy of 3 μm, whereas the latter one determines the laser profile to an extent of $\sim$15 μm. The laser beam is transported to the collision point over a distance of about 10 m using six mirrors, which are coated with a multilayer dielectric. The downstream three mirrors can be remotely controlled to adjust the laser beam at the collision point.

To maximize the luminosity of the laser- and the electron-beam collision, we optimized the laser optics as follows. The laser beam is expanded to a rms spot size of 4.7 mm and transported to the last lens, whose focal length is relatively long, i.e., 4330 mm, resulting in a collision distance of about 10 cm (see the large values of the laser β_x and β_y in Table I). Furthermore, in order to realize the head-on collision, the last mirror of 3-mm thickness is placed on the axis of the γ rays, as shown in Fig. 3. Note that the absorption of generated γ rays is negligible while passing through the mirror.

γ-ray polarimeter.—Generated γ rays were detected with both a Si photodiode with an active area of 2.8 cm$\times$2.8 cm and a thickness of 300 μm, and an aerogel Cherenkov counter having a 5-cm thickness with a refractive index of 1.015, corresponding to a kinetic-energy threshold of 2.5 MeV. An aluminum plate of 3 mm was placed in front of the aerogel Cherenkov counter to convert γ rays to electrons. The loss of γ rays before entering the magnet was about 3%, causing no difficulty for an asymmetry measurement.

The proper thickness L of the magnet was determined to maximize A^2T where $T(L)$ is the γ-ray transmittance of the magnet and $A(L)$ is the asymmetry defined before, both being described as a function of L. The values of $T(L)$ and $A(L)$ are obtained by the simulation described later. Indeed, it was found that the maximum value of A^2T was obtained for $L = 7$ cm. However, considering the current experimental condition that the experiment was carried out in the accelerator hall, and thus the detectors

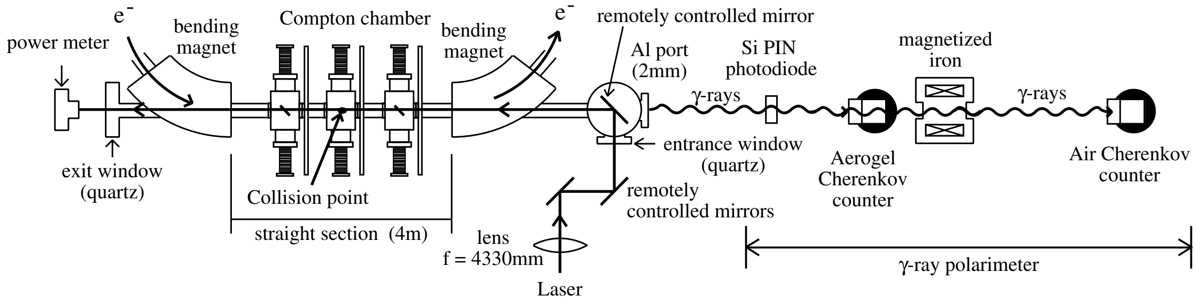

FIG. 3. Experimental setup, including the Compton chamber with three cells, the laser optics with three remotely controllable mirrors, and the γ-ray polarimeter consisting of Cherenkov counters and the magnetized iron. Laser-electron collision takes place at the central cell of the Compton chamber and the transmitted γ rays are measured with the air Cherenkov counter.

were exposed to a high level of background, we chose a thicker magnet of $L = 15$ cm to enhance the asymmetry by a factor of 2, although the time period needed for data taking was correspondingly prolonged.

It became clear through a calculation by POISSON [12] that the magnetization along the magnet axis is saturated at 2.1 T, and it rapidly drops to zero toward both ends. For maintaining the magnetization as flat as possible, we made dents at the magnet ends (see Fig. 3). Gamma rays leaving the magnet were measured with an air Cherenkov counter in front of which a lead plate of 2 mm was placed to convert γ rays to electrons and positrons. In order to select only high-energy γ rays, we maintained the air pressure to be 1 atm, corresponding to an energy threshold of 21.4 MeV. Background produced inside the magnet was dominantly attributed to Compton-scattered γ rays as well as pair-created electrons and positrons. Nevertheless, because of their angular distributions spreading over a considerably wide angular region, we can suppress these backgrounds to select only forward transmitted γ rays by making the distance between the magnet and the air Cherenkov counter sufficiently long; the distance was fixed to be 4.4 m, and therefore at the entrance of the Cherenkov counter, the background can be suppressed less than 0.1% of the signal.

Taking account of all the elements of the polarimeter shown in Fig. 3, we made various simulations to estimate the expected asymmetry with the help of the following simulation codes: CAIN [13] for the Compton scattering of electron and laser beams, whose parameters are given in Table I; GEANT3 [14] for electromagnetic interactions in materials; GRACE [15] particularly for the spin-dependent processes of electron-γ collisions in a magnet; POISSON for the magnetization of iron. The simulation program traces γ rays through the magnet and brings them into the air Cherenkov counter. The energy dependence of the efficiency (defined as the number of Cherenkov photons reaching the photomultiplier tube (PMT) generated from one γ photon) is calculated as shown in Fig. 4, where one can see the threshold at around 23 MeV being consistent with the value of 21.4 MeV derived from the formula of Cherenkov-light emission in air of 1 atm. Using the efficiency curve, the number of Cherenkov photons was counted by reversing the magnetization at a certain time interval. Upon an assumption of the 100% polarization of the laser light and the energy-dependent efficiency given in Fig. 4 as well, the simulation showed the expected asymmetry to be 1.3%. The magnitude of γ-ray polarization is proportional to the measured asymmetry and 1.3% of the asymmetry corresponds to 88% of the γ-ray polarization.

Results and conclusion.—In order to maximize the spatial overlap between the electron and laser beams, the position and the angle of the laser beam were precisely adjusted using remotely controlled mirrors, i.e., the three mirrors shown in Fig. 3. The collision timing was

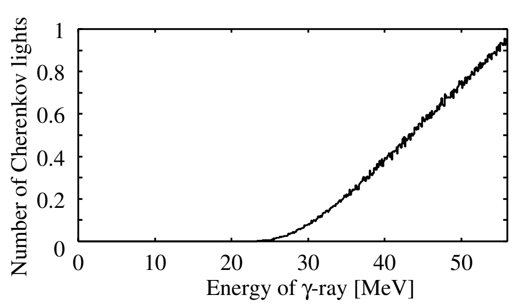

FIG. 4. Efficiency of the air Cherenkov counter, defined as the number of Cherenkov photons arriving at the PMT per one incident γ photon.

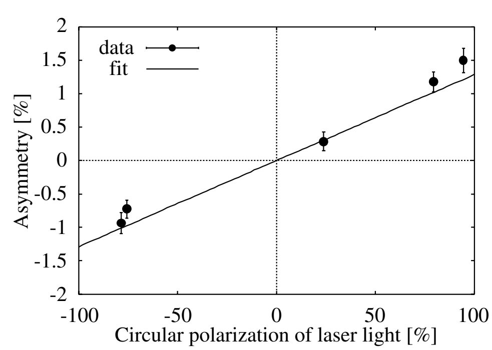

FIG. 5. Measured asymmetry as a function of the circular polarization of a laser beam at the collision point. The linear fit was made with a reduced χ^2 of 0.89.

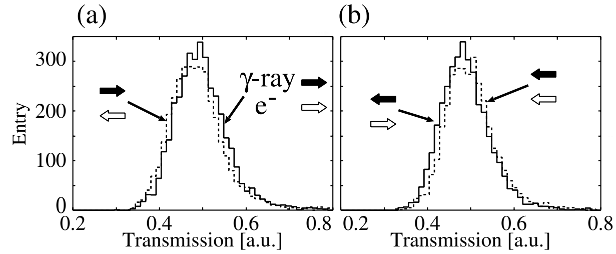

FIG. 6. Transmission of polarized γ rays passing through the magnetized iron for the cases that the γ-ray spin is parallel or antiparallel to the magnetization. The transmissions separately measured for the laser polarization of $\mp(79 \pm 1)\%$ are given in (a) and (b).

set in such a manner that the γ-ray signal became highest by changing the timing of the laser Q switch. Because a repetition rate of 1.56 Hz for the laser beam was half that of the electron beam, we were able to record alternately signals and backgrounds and thus eliminate any systematic error caused by a long-term variation of the apparatus parameters. The thus-obtained average number of γ rays was $(1.1 \pm 0.2) \times 10^6$ γs/bunch, where 0.2 is a systematic error: This is in good agreement with the values of 1.0×10^6 simulated using the beam parameters given in Table I. The magnitude of the laser-beam polarizations was measured at the collision point using a linear polarizer, a quarter-wave plate, and a photo tube.

Polarization measurements of γ rays were carried out at five different values of the laser polarizations corresponding to the data points as shown in Fig. 5. For a fixed magnitude of the laser polarization and a fixed direction of the magnetic field, a transmission measurement was carried out for 10 min and the same was made for a reversed magnetic field; this set of the measurement (20 min.) was repeated 4 times and, accordingly, 8000 collisions were recorded for a total time period of 80 min.

Figure 6(a) shows the transmission of polarized γ rays passing through the magnetized iron for left-handed lasers with a degree of the polarization of -79%. This plot was obtained in the following manner. We measured the transmission (the horizontal axis) of each γ-ray bunch produced by each collision and counted the number of bunches (vertical axis of labeled "entry") as a function of the transmission. The solid line (the dotted line) represents the case that the γ-ray spin is parallel (antiparallel) to the magnetization. The asymmetry was calculated from the shift between the center of two distributions. Figure 6(b) is the same as Fig. 6(a), except for the right-handed laser polarization of 79%.

The measured asymmetries are plotted as a function of the laser polarization in Fig. 5; the solid line represents the results of linear fitting and the intercept with the laser polarization of $\pm100\%$ is 1.29 ± 0.12, where the total error includes both the statistical and systematic errors, and the reduced χ^2 is 0.89. The experimental value of the thus-obtained asymmetry is consistent with the simulated value of 1.3%.

In conclusion, we established a transmission method which achieved the first demonstration of a polarization measurement of short-bunch γ rays. This is highly due to precise diagnostics of electron and laser beams as well as extensive simulations. We therefore accomplished a reliable description of the whole experimental processes incorporating collisions of laser and electron beams as well as γ-ray polarimetry. Technical information accumulated in this study shall allow us to design a positron polarimetry which will soon be put into practical use, leading to the final step of the proof-of-principle experiment for the proposed scheme of a polarized positron source.

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