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Photon spectrum and polarization for high conversion coefficient in the Compton backscattering process

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ABSTRACT

This study looks to simulate the nonlinear Compton backscattering (CBS) process based on the Monte Carlo technique for the conversion coefficient $K_c \geqslant 1$, which can be considered as the average number of photons emitted by each electron. The characteristics of the nonlinear CBS process simulated in this work are as follows: the number of absorbed photons of a laser, the distance in the laser pulse in which the electron passes between two collisions, the energy and the polarization of the emitted photon in each collision, and the polarization of the electron before and after collision. The developed approach allows us to find the spectra and polarization characteristics of the final electrons and photons. When $K_c > 1$, the spin-flip processes need to be considered for a correct simulation of the polarization of the final photons and electrons for energies typical of a γ-γ collider.

1. Introduction

Following the discovery of the Higgs-like boson, the characteristics of various kinds of colliders are being considered for detailed study (e.g. a γ-γ collider with high luminosity [1,2]). The project SAPPHiRE [2] is expected to receive γ-beams in the scattering of laser photons with energies of $\hbar\omega_0 = 3.53$ eV by electrons with an energy of $E_0 = 80$ GeV, which produces γ-rays with a peak energy of $\hbar\omega \sim 65$ GeV. To achieve the desired luminosity (e.g. $L_{\gamma\gamma} \sim 3.6 \times 10^{33}$ cm^{-2} s^{-1}), the use of a laser with a peak power of $W_L = 6.3 \times 10^{17}$ W/cm^2 is assumed. The authors [2] have estimated the output of scattered photons, $N_\gamma = 1.2 \times 10^{10}$ photons/bunch, for an electron bunch population $N_e = 10^{10}$, for the following electron beam parameters: $\sigma_x \times \sigma_y = 400\,\text{nm} \times 18\,\text{nm}$; the degree of circular polarization of the laser photons, $P_c = -1$; and the longitudinal polarization of the electron beam, $P_e = 0.8$. The photon yield per an initial electron is characterized by the so-called conversion coefficient [3,4]:

$$K_c = N_\gamma / N_e, \tag{1}$$

where $N_\gamma = L_{e\gamma}\sigma$ is the number of scattered photons, $L_{e\gamma}$ is the luminosity characterized by the colliding laser and electron beams, and σ is the Compton scattering cross-section for a given energy of the laser photon $\hbar\omega_0$ and the electron with energy $E_0 = \gamma_0 mc^2$. The conversion coefficient for the project [2] achieves the value $K_c = 1.2$.

2. Theory

For the head-on collision between laser and electron bunches—which are described by three-dimensional Gaussian distributions with fixed parameters—the luminosity is calculated analytically and does not depend on the length of the colliding bunches [4]:

$$L = \frac{N_e N_L}{2\pi\sqrt{\sigma_{Lx}^2 + \sigma_{ex}^2}\sqrt{\sigma_{Ly}^2 + \sigma_{ey}^2}}. \tag{2}$$

In (2), $\sigma_{Lx(y)}$ and $\sigma_{ex(y)}$ describe the transverse sizes of the colliding beams (L and e indexes correspond to the laser beam and electrons, respectively); N_L is the total number of photons in the laser pulse; and β_0 is the speed of electrons in a bunch.

For the simplest case of azimuthally symmetric beams, ($\sigma_{Lx}^2 = \sigma_{Ly}^2 = \rho_L^2/2; \sigma_{ex}^2 = \sigma_{ey}^2 = \rho_e^2/2; \rho_L, \rho_e$ are the radii of the laser and electron beams at the interaction point) under the condition $\rho_e \ll \rho_L$ instead of Eq. (2), we obtain a simple formula:

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$$L \approx \frac{2N_e N_L}{\pi \rho_L^2}. \quad (3)$$

Thus, from the formulas (2) and (3), the conversion coefficient can be estimated, which depends on the length of the laser pulse (in other words, on the thickness of the light target [5]):

$$K_c = \frac{2N_L \sigma}{\pi \rho_L^2} = 2n_0 \sigma \ell_L, \quad (4)$$

where $\ell_L = c\tau_L$ is the effective length of the laser pulse, and n_0 is the concentration of the laser photons.

The effective length of the laser pulse can be expressed in terms of the laser wavelength λ_0 and the number of periods N_0:

$$\ell_L = \lambda_0 N_0. \quad (5)$$

If the thickness of the light target is expressed through the so-called 'collision length',

$$\ell_c = \frac{1}{2n_0 \sigma},$$

the Eq. (4) can be written as follows:

$$K_c = \ell_L / \ell_c.$$

The concentration of the laser photons n_0 at the interaction point is determined by the field intensity of the laser pulse

$$n_0 = \frac{a_0^2}{4\alpha \lambda_e^2 \lambda_0} \quad (6)$$

Here, α is the fine structure constant, λ_e is the Compton wavelength of an electron, and a_0 is the laser strength parameter which can be estimated by the 'engineering' formula [6]

$$a_0 = 0.85 \lambda_0[\mu\mathrm{m}] \sqrt{\frac{W_L[\mathrm{W/cm^2}]}{10^{18}}}, \quad (7)$$

where W_L is the laser intensity.

After substituting Eqs. (5) and (6) into (4), we obtain

$$K_c = \frac{\alpha}{2} a_0^2 \frac{\sigma}{r_0^2} N_0. \quad (8)$$

Eq. (8) is based on the assumption of a constant cross-section along the trajectory of the electron in the light target. In this approximation, the conversion coefficient K_c is the mean number of collisions $\bar{k}$ of the initial electron with photons of the laser pulse. This approximation becomes incorrect if the electron experiences multiple collisions with laser photons, which would result in the loss of a significant part of its energy in each collision. As the energy of the electron decreases, the cross-section of the Compton scattering increases—and hence, the distance between two successive collisions in the light target decreases (see, for example, [7]).

The cross-section of the nonlinear Compton scattering, which depends on the parameter a_0, is the sum of the cross-sections $\sigma^{(n)}$, each of which describes the process:

$$p_0 + nk_0 = p_1 + k_1,$$

where the initial electron 'absorbs' n number of laser photons and emits one hard γ-quantum. Four momenta of the initial and final electron (photon) are designated as $p_0(k_0), p_1(k_1)$.

A detailed description of nonlinear Compton scattering with the polarization states of the initial and final particles is given elsewhere [8].

Based on equations from [8], we can write the cross-section of the nonlinear Compton scattering of polarized electrons with the spin-flip effect, and without taking into account the polarization of the scattered γ-quanta:

$$\frac{d\sigma^{(n)}}{dy} = \frac{d\sigma_1^{(n)}}{dy} + \zeta_{0z} P_c \frac{d\sigma_2^{(n)}}{dy} + \zeta_z P_c \frac{d\sigma_2^{(n)}}{dy} + \zeta_z \zeta_{0z} \frac{d\sigma_3^{(n)}}{dy}, \quad (9)$$

where ζ_{0z} and ζ_z are the longitudinal polarization of the initial and final electrons, respectively, and P_c is the circular polarization of the laser photons. The cross-section $d\sigma_1^{(n)}/dy$ describes interaction of unpolazrized initial particles summarized over spin states of the final particles, the cross-section $d\sigma_2^{(n)}/dy$ describes interaction of polarized photons with polarized electrons, and the cross-section $d\sigma_3^{(n)}/dy$ describes interaction for the fixed polarization states of the inital and final electrons (see formula (32) and (33) in [8]).

In Eq. (9), standard variables are used:

$$x_0 = \frac{2p_0 k_0}{(mc^2)^2} = \frac{4\gamma_0 \hbar\omega_0}{mc^2},$$

$$y = \frac{k_0 k_1}{p_0 k_0} = \frac{\hbar\omega}{\gamma_0 mc^2} = \frac{\hbar\omega}{E_0}.$$

The last expressions were obtained by the ultra-relativistic approximation.

The maximum value of the variable y in the reaction involving n number of laser photons is determined by the following condition:

$$y = y_{\max}^{(n)} = \frac{nx_0}{1 + nx_0 + a_0^2/2}. \quad (10)$$

Cross-sections $d\sigma_i^{(n)}/dy$ can be calculated using expressions presented elsewhere [8].

The cross-section without spin-flip for the considered photon polarization state $P_c = -1$ is defined as:

$$\frac{d\sigma_{11}^{(n)}}{dy} = \frac{d\sigma_1^{(n)}}{dy} - 2\frac{d\sigma_2^{(n)}}{dy} + \frac{d\sigma_3^{(n)}}{dy} \quad (11)$$

for the transition $< \zeta_{0z} >= +1 \to \zeta_z = +1$, and

$$\frac{d\sigma_{22}^{(n)}}{dy} = \frac{d\sigma_1^{(n)}}{dy} + 2\frac{d\sigma_2^{(n)}}{dy} + \frac{d\sigma_3^{(n)}}{dy} \quad (12)$$

for the transition $< \zeta_{0z} >= -1 \to \zeta_z = -1$.

From Eq. (9), we obtained the cross-section for the spin-flip process; it is the same as for both kinds of transitions $1 \to 2$ and $2 \to 1$:

$$\frac{d\sigma_{12}^{(n)}}{dy} = \frac{d\sigma_{21}^{(n)}}{dy} = \frac{d\sigma_1^{(n)}}{dy} - \frac{d\sigma_3^{(n)}}{dy}. \quad (13)$$

See, for instance, Fig. 1, where the spin-flip cross-section is presented for $n = 1$. One can see that such a cross-section can achieve about 40% from the cross-section without spin-flip for our case $E_0 = 80$ GeV.

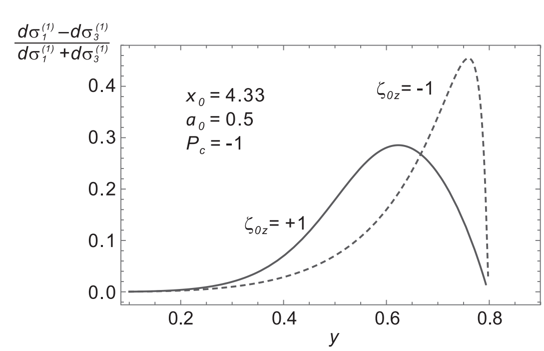

Fig. 1. Spin-flip cross-section, calculated for $n = 1, k_0 = 4.33$ and $a_0 = 0.5$.

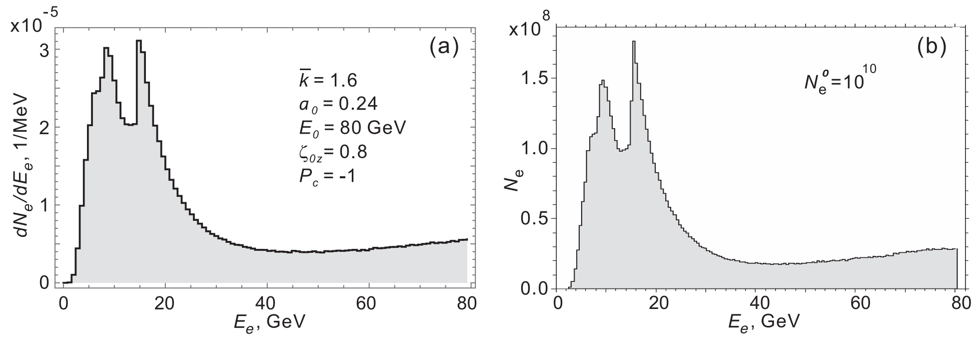

Fig. 2. Spectra of scattered electrons with high conversion coefficient.

Table 1
Simulation parameters.

Electron energy, E_0 (GeV)	80
Laser photon energy, $\hbar\omega_0$ (eV)	3.53
Laser photon polarization, P_c	−1
Initial electron polarization, ζ_{0z}	0.8
Laser strength parameter, a_0	0.24
Conversion coefficient, K_c	1.6

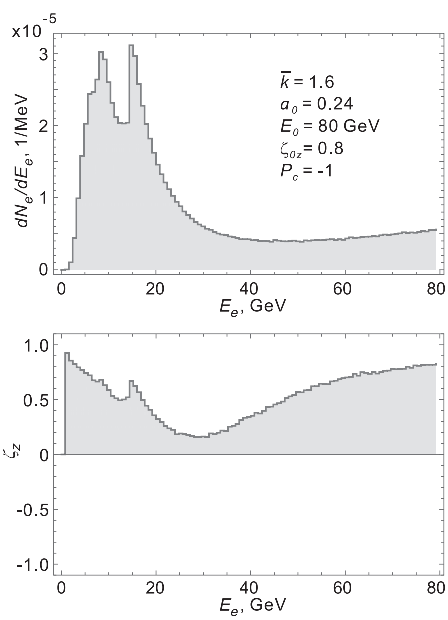

Fig. 3. Spectra and polarization of scattered electrons.

The cross-section of the considered process ($\zeta_{0z} = +1; P_c = -1$), regardless of the polarization states of the final particles, can be expressed by Eqs. (11) and (13) as follows:

$$\frac{d\sigma^{(n)}}{dy} = \frac{d\sigma_{11}^{(n)}}{dy} + \frac{d\sigma_{12}^{(n)}}{dy} = 2\left(\frac{d\sigma_1^{(n)}}{dy} - \frac{d\sigma_2^{(n)}}{dy}\right). \tag{14}$$

Following the integration of Eq. (14) over $y^{(n)}$ in the limits $0 \leqslant y^{(n)} \leqslant y_{\max}^{(n)}$, one can obtain a partial cross-section of the nonlinear Compton backscattering (CBS) process, which describes the process involving the 'absorption' of n laser photons:

$$\sigma^{(n)} = \int_0^{y_{\max}^{(n)}} \frac{d\sigma^{(n)}}{dy^{(n)}} dy. \tag{15}$$

The total cross-section is defined by the sum of the 'partial' cross-sections:

$$\sigma = \sum_{n=1}^{n_{\max}} \sigma^{(n)}. \tag{16}$$

For the SAPPHiRE project, $a_0 = 0.237$ [2]. For the cases currently under consideration, one can choose $n_{\max} = 3$, given the ratio $\sigma^{(3)}/(\sigma^{(1)} + \sigma^{(2)} + \sigma^{(3)}) = 0.007$.

If the conversion coefficient K_c is approximately equal to unity, it then means that an electron, in passing through the laser pulse, can experience several successive collisions with laser photons and emit a hard photon with each collision.

Knowing the cross-sections (11)–(13), we calculate probabilities of a collision with and without spin-flip process for each interaction.

The cross-section σmay change after each collision, due not only to the decrease in energy, but also because of the spin-flip processes (see Eq. (13)).

In the process of the Compton scattering of laser photons with a circular polarization P_c by longitudinally polarized electrons (i.e. degree of polarization $\zeta_z = \pm 1$), the scattered photons can have a circular polarization of both the right and left. The probability of emission of a photon with right (left) polarization is determined by the following relation:

$$dW_{R(L)} = \frac{1}{2}\left(1 \pm \frac{F_2^{(n)}}{F_0^{(n)}}\right), \tag{17}$$

and circular polarization is given by $P_c = (dW_R - dW_L)/(dW_R + dW_L)$.

The probability of scattered electrons to get polarization $\zeta_z = +1$ or $\zeta_z = -1$ is defined as follows:

$$dP_{+1(-1)} = \frac{1}{2}\left(1 \pm \frac{G_3^{(n)}}{F_0^{(n)}}\right). \tag{18}$$

The functions F_0, F_2, and G_3 for the nonlinear process can be found in the same work [8].

To achieve the correct simulation of the multiple CBS process—together with the aforementioned change in the cross-section and the polarization state of the electron—we used the Monte Carlo technique with the following algorithm:

- simulation of the initial polarization state of the electron (in the case of partial polarization of the incident beam);
- based on the known value of the cross-section, the value of ℓ_c (collision length) is simulated from the exponential distribution $P(\ell) = \sum \exp(-\sum \ell)$ with the macroscopic cross-section $\sum = 2n_0\sigma$;
- in the next collision, the probability of the spin-flip process is simulated (generation of $\zeta_z = \pm 1$);

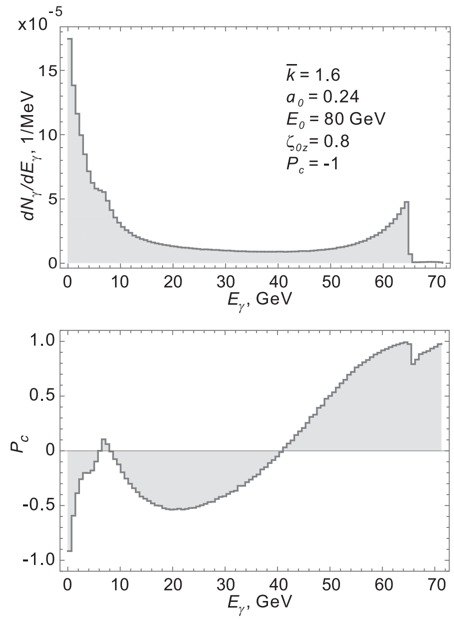

Fig. 4. Spectra and polarization of emitted photons.

- afterwards, the simulation of energy of the γ-quanta is performed in accordance with the cross-section of Eqs. (12)–(14);
- simulation of the circular polarization of the emitted photon.

The process stops when the total length of the paths between successive collisions exceeds the thickness of the light target ℓ_L.

During the simulation of the nonlinear Compton scattering process, the following parameters are taken into account: $x = 4\gamma\hbar\omega_0/mc^2$, and the longitudinal polarization ζ_z which is determined after each collision by including the probability of the spin-flip process. Furthermore, the energy of the emitted $\hbar\omega$ quanta (or value $y = \hbar\omega/(\gamma_0 mc^2)$) and its polarization state are simulated.

As an example of the developed algorithm, a simulation of the process of nonlinear Compton scattering of circularly polarized laser photons by initially polarized electrons, with $\zeta_{0z} = +0.8$ passing through the light target with the mean number of scattered photons $K_c = 1.6$, was performed (see Fig. 2). Simulation was performed for the parameters presented in Table 1.

Fig. 2(a) shows only the spectrum of interacted electrons. The simulation which uses CAIN code [9] shows such a distribution, in Fig. 2(b).

While comparing the distributions obtained by the CAIN code, through the developed approach, we can see that there is reasonable agreement.

The simulation results of the polarization characteristics of the electrons and photons with the parameters specified in Table 1 are shown in Figs. 3 and 4.

3. Conclusion

The detailed analysis of polarization characteristics for the Compton backscattering (CBS) process for projects ELI-NP [10] and SPARC [11] was performed in the paper [12]. The authors used analytical description of the linear CBS process. Our approach allows to simulate polarization characteristics for both processes the linear and nonlinear with taking into account the energy losses of the initial electron during subsequent interaction with laser photons.

Authors of the work [13] have calculated circular polarization of the final photons for scattering on polarized electrons for the linear CBS process only.

We have developed the approach which allows to include into consideration the nonlinear CBS process taking into acount spin-flip processes.

In conclusion, we deduced the following:

1. The multiple Compton scattering process is stochastic, and it is characterized by the distribution of the number of collisions involved (i.e. the number of emitted photons), spectra and polarization of scattered photons and electrons. The average value of the number of emitted photons does not typically coincide with the thickness of the light target, expressed in collision lengths, and is calculated for the electron with initial energy.
2. For each laser pulse duration, there is a nonzero probability of passage of the initial electron beam without having any interaction with the laser photons. This part depends on the thickness of the light target (e.g. for one collision length target, such a part is approximately 30% of the initial intensity). This fact needs to be taken into account when designing the beam-dump for a beam of secondary electrons.
3. The contribution of the trajectories of electrons with a number of collisions leads to the substantial enrichment of the spectrum of resulting 'soft' photons that need to be considered when calculating luminosity.
4. The Monte Carlo technique developed in this study allows for the simulation of the polarization characteristics of photons and electrons while taking into account spin-flip processes.

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