Production of high-energy colliding $\gamma\gamma$ and γe beams with a high luminosity at VLÉPP accelerators

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Colliding $\gamma\gamma$ and γe beams with an energy and luminosity of the same order of magnitude as for e^+e^- beams can be produced by scattering a laser light at the accelerators with colliding e^+e^- beams with an energy $\gtrsim 100$ GeV. Such accelerators are currently in the design stage.

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1. The reactions $\gamma\gamma \to$ hadrons and $\gamma e \to e +$ hadrons, which are studied at linear accelerators with e^+e^- beams in the collision of virtual photons, have recently attracted considerable interest.[1] In this letter we show that direct $\gamma\gamma$ and γe collisions with a high energy and luminosity can be used to study these reactions.

It is clear that colliding e^+e^- beams with an energy $E \gtrsim 100$ GeV can be produced only at linear accelerators.[2] Such accelerators are currently in the design state in Novosibirsk [(VLÉPP, $E = 100$–300 GeV (Ref. 2)] and in the U.S.A. [SLAC Linear Collider (SLC), $E = 50$ GeV (Ref. 3)]. The fundamentally new feature of these accelerators is that their $e^\pm$ beams are used only once [at a low repetition rate $\nu = 10$ Hz (Ref. 2) or 180 Hz (Ref. 3)]. If a large fraction of electrons are converted to photons, then the luminosity of $\gamma\gamma$ or γe collisions produced in this manner will be close to that of the e^+e^- collisions, $L_{ee} \sim 10^{32}$ cm^{-2} sec^{-1}. This simple concept is the basis of our study (see Ref. 4).

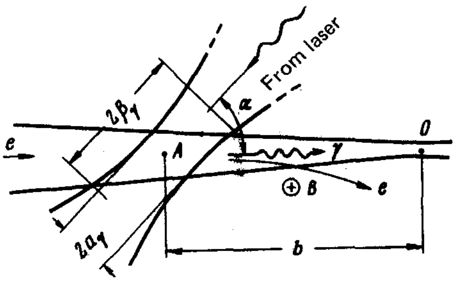

FIG. 1.

2. The high-energy photons can be obtained by Compton scattering of a laser light by an electron beam. This well-known method[5] has been used at SLAC.[6] However, the coefficient k for internal conversion of electrons into photons, which was determined at SLAC (Ref. 6), is very small ($\sim 10^{-7}$). Because of the very small size of electron bunches (length $l_e = 2$–4 mm, radius at the collision point $a_e = 1.25$–1.4 μm, a value of $k \sim 1$ has been obtained in Refs. 2 and 3 at a moderate energy of the laser flash, $A \sim 10$ J.

The proposed arrangement is as follows (Fig. 1): A laser light is focused on an electron beam in the conversion region A a short distance, $b \sim 10$ cm, from the collision point 0; after scattering by electrons, the highly energetic photons move almost longitudinally along the original electron trajectories, i.e., they are focused at the collision point 0. The electrons, however, are deflected by a magnetic field, $B \sim 10$ kG, from the collision point. The produced γ beam subsequently collides with a bucking electron beam or a similar γ beam.

3. The scattering of a photon with an energy ω_0 by an electron with an energy E occurs at a small collision angle α in the conversion region. The majority of the scattered photons move along the electron trajectories at small angles θ. The energy ω of these photons is

$$\omega = \frac{\omega_m}{1 + (\theta/\theta_0)^2}, \quad \omega_m = \frac{x}{x+1} E, \quad \theta_0 = \frac{m_e c^2}{E} \sqrt{x+1},$$
$$x = \frac{4 E\omega_0}{m_e c^2} \cos^2 \frac{\alpha}{2}. \tag{1}$$

The energy spectrum of the scattered photons is described by a well-known cross section (see Fig. 2)

$$\frac{d\sigma}{dy} = \frac{2\sigma_0}{x}\left[\frac{1}{1-y} + 1 - y - \frac{4y}{x(1-y)} + \frac{4y^2}{x^2(1-y)^2}\right],$$
$$y = \frac{\omega}{E}, \quad \sigma_0 = \pi\left(\frac{e^2}{m_e c^2}\right)^2. \tag{2}$$

We see that the energy distribution of photons is rather broad. The electrons with energies $\omega > \omega_m/2$ move at angles $\theta < \theta_0$.

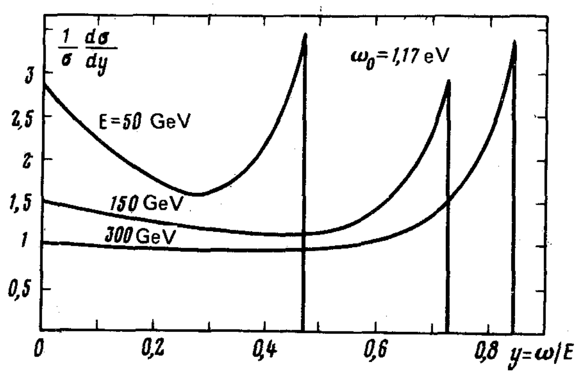

FIG. 2.

If the laser light or the electron is polarized, then the γ beam is also polarized.

For further estimates we shall assume that $\omega_0 = 1.17$ eV (with neodymium glass laser $\lambda = 1.06$ μm) and $E = 150$ GeV. In this case $x = 2.69$, $\omega_m = 109$ GeV, $\theta_0 = 0.65 \times 10^{-5}$ rad, and $\sigma = 2.5 \times 10^{-25}$ cm^2.

4. The distribution of the electron-beam density in the transverse direction is generally Gaussian. A good focusing of the laser light is also obtained by means of Gaussian beams. The rms radii of the beams are

$$r_e = a_e\sqrt{1 + b^2/\beta_e^2}, \qquad r_\gamma = a_\gamma\sqrt{1 + z^2/\beta_\gamma^2}\,. \tag{3}$$

Here a_e and β_e are the radius and the beta function of the electron beam in the collision region, $\beta_e = 1$ cm (Refs. 2 and 3), a_γ is the radius of the laser beam in the focus, z is the distance from the focus along the beam axis, the magnitude of the region with a high photon density $2\beta_\gamma$ is determined by the diffraction, and $\beta_\gamma = 2\pi a_\gamma^2/\lambda$. For an important case $4\beta_\gamma > l_e + l_\gamma$ (l_e and $l_\gamma = c\tau$ are the lengths of the beams) the internal conversion coefficient k is expressed in terms of the laser-flash energy A

$$k = \frac{A}{A_0}, \qquad A_0 = \frac{\pi(r_e^2 + a_\gamma^2)}{\sigma}\,\omega_0. \tag{4}$$

This formula, which is valid for $A \ll A_0$ with $A \approx A_0$, gives a good estimate (its derivation and other cases have been analyzed in Ref. 7). The result of (4) can be explained in the following way. To overlap the entire area of the electron beam, $\sim\pi r_e^2$, we must have $\sim\pi r_e^2/\sigma$ photons with $a_\gamma \sim r_e$; i.e., for $k \sim 1$ we must have the energy $A \sim (\pi r_e^2/\sigma)\omega_0$.

At $b = 10$ cm we have $r_e = 12.5$ μm for VLEPP. For $a_\gamma = 20$ μm we have $4\beta_\gamma = 1$ cm and, according to (4), $A_0 = 15$ J for a pulse-flash duration $\tau < 4\beta_\gamma/c = 30$ psec. We see from this that $k \sim 1$ can be obtained in single pulses in the existing lasers [there are lasers with $A = 300$–1000 J, with $\tau = 30$–100 psec (Ref. 8)]; the indicated size of the focal spot was used in Ref. 9, where $a_\gamma = 17$ μm at $A = 14$ J and $\tau = 140$ psec).

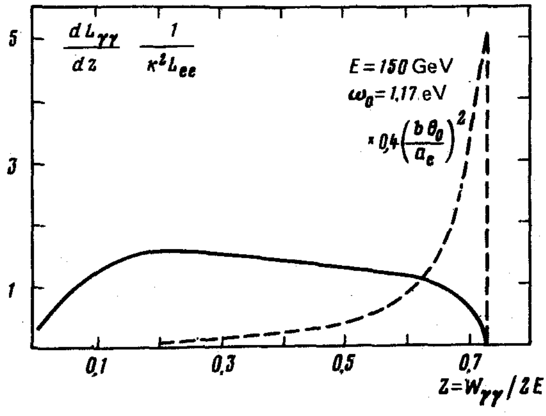

FIG. 3.

We must note the production ray of hadrons in $\gamma\gamma$ collisions is proportional to the product $\nu k^2 \sigma$ ($\gamma\gamma \to$ hadrons). Since $\sigma(\gamma\gamma \to \text{hadrons}) \sim (10^4 - 10^5)\, \sigma(e^+e^- \to \text{hadrons})$ in the analyzed energy region, the $\gamma\gamma$ beams produced at $k \sim 0.1$ (i.e., $A \sim 1.5$ J) and $\nu = 10$ Hz or at $k \sim 1$ and $\nu = 0.1$ Hz are of great interest from the physical point of view.

5. The relative increase in the area of the γ beam due to Compton scattering has been rather modest, $\sim(b\theta_0/a_e)^2$ (at $b = 10$ cm it is equal to 0.27); the total luminosities of γe and $\gamma\gamma$ collisions are $L_{\gamma e} = kL_{ee}$ and $L_{\Gamma\gamma} = k^2 L_{ee}$. In the γe collisions the distribution of luminosity over the square of the invariant mass $W_{\gamma e}{}^2 = 4E\omega$ coincides with $d\sigma/d\omega$ (see Fig. 2). The distribution of luminosity in the invariant mass $W_{\gamma\gamma}$ in the case of $\gamma\gamma$ collisions is represented by the solid curve in Fig. 3. It can be seen that these distributions are very broad.

6. Since the lower-energy photons are deflected stronger from the direction of motion of the original electrons as a result of Compton scattering [see Eq. (1)], the density of soft photons in the collision region is low at $(b\theta_0/a_e)^2 \gg 1$, and only the collisions of hard photons are important. This leads to a noticeable monochromatization. The distribution of luminosity in $W_{\gamma\gamma}$ for this case is represented by the broken curve in Fig. 3. Half of the luminosity is concentrated in the interval $\eta = \Delta W_{\gamma\gamma}/W_{\gamma\gamma\max} = 9\%$. As x is increased, the monochromatization improves; a numerical calculation for $x = 1$–20 gives $\eta = 0.84/(x+7)$.

As b is increased, the luminosity decreases as $(A/A_0)^2/b^2$; according to Eqs. (3) and (4), $A_0 \propto b^2$ (when $a_\gamma \sim r_e$). The selection of b from the condition $(a_e/b\theta_0)^2 \sim \eta$ yields the maximum luminosity without a loss of monochromatization. A luminosity $L_{\gamma\gamma}/2 \approx 0.04k^2 L_{ee}$ (at $x = 1$–20) in this case is concentrated in the interval $\sim\eta$. A monochromatization $\eta \sim 10\%$ is attained at $b = 60$ cm in the case under consideration; this corresponds to a laser flash is required for monochromatization of the luminosity. We should note that $A_0 \propto a_e{}^4/\beta_e{}^2$ and $L_{\beta\gamma} \propto A^2 \beta_e{}^4/a_e{}^{10}$ in the case under consideration; i.e., a small change in the accelerator's parameters improves the situation considerably. The value of a_e theoretically can be reduced for $\gamma\gamma$ collisions because of the absence of the collision effects which are present in the e^+e^- collisions.

A more detailed discussion of the problems raised by us, including those pertaining to the background and measurement of luminosity, is contained in Ref. 7.

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