High Energy Gamma Sources with Small Energy Spread. Possible Schemes.

A.A.Varfolomeev
Russian Research Center 'Kurchatov Institute', Coherent Radiation Lab. 123182 Moscow, Russia

Abstract

The problem of obtaining of quasimonochromatic and collimated high energy γ beams for future γ–γ colliders is considered. Two different schemes are analyzed: Compton back scattering of laser beam and annihilation of electron-positron pairs.

INTRODUCTION

High energy γ beams can be obtained with any kind of conversion of electron beams: bremstrahlung, electron-positron annihilation or Compton scattering. All these approaches were analyzed during last decades. Due to the progress in high power lasers (both conventional and free electron lasers) Compton backscattering scheme becomes the most attractive. The main physical idea to generate high energy photons with the Compton backscattering of intense laser beam was first published in sixties [1] and later in eighties was proposed to be used for obtaining intense colliding beams [2]. The idea is intensively developing now (see for example [3],[4]).

The central problem for the gamma colliding beams is the luminosity and energy spread. It was shown in some papers that high luminosity levels $L_{\gamma\gamma} > 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ can be obtained what is comparable with that of primary electron collider luminosity [2]. As concerning the energy spread there is a limit connected directly with the elementary scattering process. It is defined by the limited angular size of the γ-beam.

In this paper two schemes of γ sources are analyzing. The first is a Compton backscattering process. The second is a novel scheme with using high intensity laser beam for stimulating annihilation process of interacting e^+e^- beams. It is shown that both schemes could be perspective for high energy γ-γ colliders with high luminosities.

COMPTON BACKSCATTERING ON HIGH ENERGY ELECTRON BEAMS

Kinematic scheme of the head on colliding electron and laser beam is shown in fig.1.

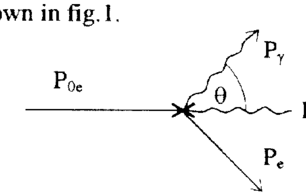

Figure 1.

$P_{oe}(P_e)$, $P_{o\gamma}(P_\gamma)$ - are the momenta of the incoming electron (outcoming electron) and the incident photon (outgoing photon) respectively. θ is the angle between the outgoing photon and the incident electron momenta.

For small angles θ the energy of the emerging γ quantum ω is determined by the formulae

$$\omega = \frac{4\gamma^2\omega_0}{1+(\gamma\theta)^2+z} \tag{1}$$

where ω_0 is the incident laser photon energy; $\gamma = E/m$ is the relativistic factor of the electron; $z = 4\gamma^2\omega / E$ is the recoiling factor. The spectrum of the ω defined by the well known Klein-Nishina formula is wide [1],[5]. By quanta collimating a narrow band can be selected. From (1) it follows that with a small deflection angle $\theta<\theta_m<1/\gamma$ outgoing γ quantum beam will be quasimonochromatic with small energy spread given by

$$\frac{\Delta\omega}{\omega_m} = (\gamma\theta_m)^2 \tag{2}$$

where $\omega_m = 4\gamma^2\omega_0/(1+z)$ is the maximum energy of the γ quanta. If no focusing of the laser beam takes place the reasonable limits for the small angle acceptance θ_m is determined by the normalized emittance of the electron beam $\varepsilon_n = \pi\sigma\sigma'\gamma$. The limit for the energy spread selection is approximately equal to

$$\frac{\Delta\omega}{\omega_m} = \left(\frac{\varepsilon_n}{\pi\sigma_x\gamma}\right)^2 \tag{3}$$

For up-to-date obtainable emittance $\varepsilon_n \sim 10\ \pi$ mm mrad monochromatic beams with $\Delta\omega/\omega_m \sim 10^{-2}$ are achievable within acceptance angle $\sim 0.1\ \gamma^{-1}$.

Since the energy spectrum of γ quanta is wide the limits (2) mean cutting of the total intensity by one-two orders. If some focusing of the interacting laser beam takes place then the selection (2) is not efficient and quasimonochromatic beams are not obtainable. For this case only conventional wide energy spread beams are produced.

Another very important characteristic of the collider is its luminosity L which is proportional to colliding beam densities.

Spectral luminosity $dL/d\omega_c$ i.e. luminosity calculated per unit frequency interval of the colliding γ quanta $\omega_c = \sqrt{\omega_1\omega_2}$ have been found for electron beams interacting with focused laser beams [4],[6]

$$\left(\frac{dL_{\gamma\gamma}}{d\omega_c}\right)_{max} \le \frac{L_{ee}}{\omega_m} \tag{4}$$

Here ω_m is the maximum energy of the backscattered γ quanta and L_{ee} is the respective luminosity of the primary electron beams. From the above it follows that for the

Compton backscattering spectral luminosity of γ quanta beams within small energy spread will be at least some orders lower than luminosity of the primary electron beam. Since that the conventional Compton backscattering schemes can not provide γ beams with small energy spread and high intensity comparable with that of primary electron beams.

As was shown earlier in [7] the angular and frequency distribution of scattered quanta depends on the electron trajectory in the Compton scattering process. We have found by simulations that for some kinds of trajectories (provided by special undulators) radiation at larger angles θ can be suppressed. Fig.2 illustrates the effect of a spiral electron trajectory and noncollinear sectioned trajectories. It is evident from these results that some reserves for higher spectral luminosities of backscattered quanta beams do exist.

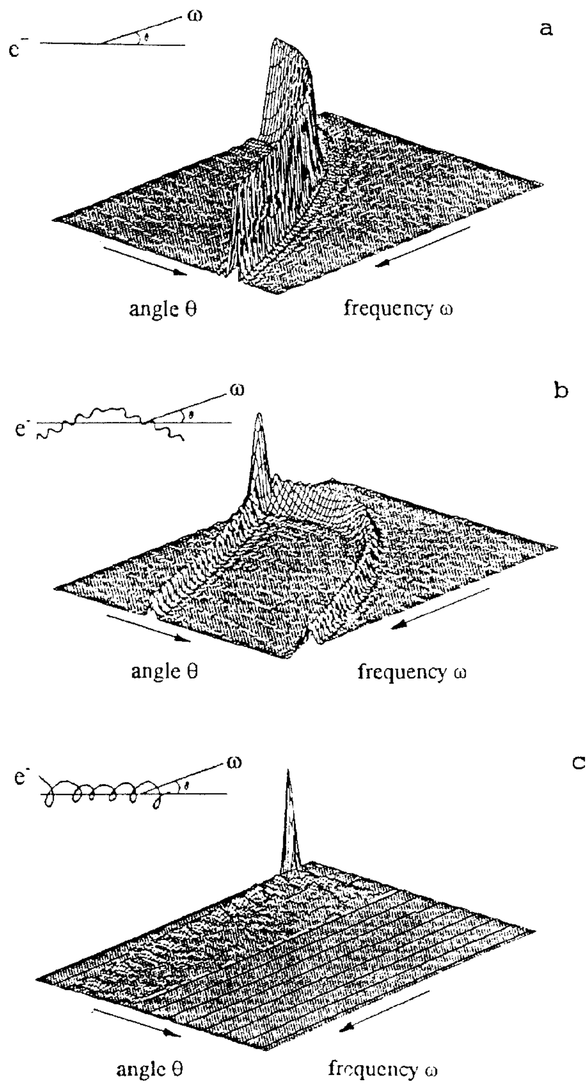

Figure 2. Radiation Intensity Spectrum of electrons undulating with frequency ω_c (backscattered photon imitation) for different kinds of macroscopic electron trajectories in the interaction area

a. Straight line of finite length.

b. Two straight sections inclined to one axis.

c. Spiral trajectory.

STIMULATED ELECTRON-POSITRON ANNIHILATION

Now we would like to analyze a novel scheme . It is based on the same key components: high energy electron and positron beams and high power laser beams. The process is the two photon annihilation stimulated by the laser field ω_0

$$e^+ + e^- \rightarrow \omega_\gamma + \omega_0 \qquad (5)$$

The principal scheme is illustrated by Fig.3

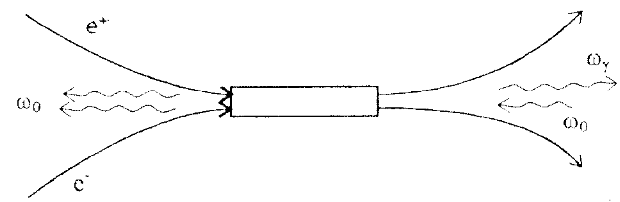

Figure 3

Electron and positron beams having equal energies E_x=E_y=γmc^2 are entering into interaction region. From kinematics it follows that in forward direction a high energy quantum is emerging with $\omega_\gamma \leq 2\gamma m$ accompanying by a soft quantum $\omega_0 = m/2\gamma$ outgoing in opposite direction. The key point is an outer high power beam of lower frequency ω_o stimulating the process by many orders of magnitude.

The Feinman diagrams of the two photon annihilation process are given by Fig.4.

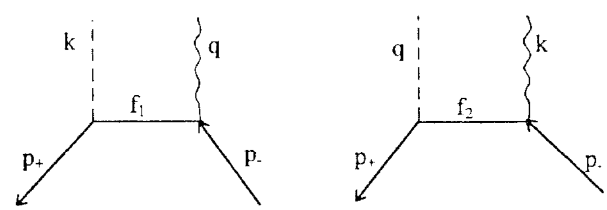

Figure 4

where $p_-(p_+)$ is the electron (positron) momentum; k is the γ quanta momentum; q is the momentum of photon; $f_1 = -p_+ + k$; $f_2 = -p_+ + q$. The matrix element for the process can be written in standard way as follows [8]

$$\langle f|S|i\rangle = \frac{ie^2 A}{2\sqrt{\omega\omega_s}\,2\sqrt{E_+E_-}}\frac{1}{V^2}\{\bar{u}Qu\}(2\pi)^4\delta(p_+ + p_- - k - q), \qquad (6)$$

where $$Q = \bar{u}(-p_+)\left\{\hat{e}\frac{i\hat{f}_1 - m}{m^2\kappa_1}\hat{e}_s + \hat{e}_s\frac{i\hat{f}_2 - m}{m^2\kappa_2}\hat{e}\right\}u(p_-)$$

Here u(-p₊), u(p₋) are spinors $m^2\kappa_1 = -2p_+k$; $m^2\kappa_1 = -2p_+k$; ω, ω_s - frequencies of the quanta; E_+ E_- energies of the positron and electron respectively. The unit system $\hbar$=c=1, $e^2/4\pi$ = 1/137 is used as in [8]. For A=1 all four fields are normalized for one respective particle in the interaction volume V. If we consider the field ω_o as stimulating one then its intensity should be much higher.

$$A = \sqrt{\left(\frac{I_s}{s\omega_o}V + 1\right)} \qquad (7)$$

where I_s is the intensity of the laser field ω_0, s is the cross section of the interaction area. The stimulating factor is equal to A^2 (Einstein factor).

The probability of the stimulated process follows from (6)

$$dW_{if} = \frac{1}{8}\sum_{\mu i}\left|\bar{u}Qu\right|^2 \frac{2\pi e^4 I_s}{16\omega\omega_s^2 E_+E_- Vs}\delta(p_+ + p_- - k - k_s)d\vec{k} \quad (8)$$

Here $(1/8)\sum_{\mu i}$ means summation of final polarization states of k-quantum and averaging over polarization and spin stages of other 3 particles respectively. Spur of Dirac matrices can be found in [7]

$$\frac{1}{8}\sum_{\mu i}\left|\bar{u}Qu\right|^2 =$$

$$= -\left\{4\left(\frac{1}{\kappa_1}+\frac{1}{\kappa_2}\right)^2 - 4\left(\frac{1}{\kappa_1}+\frac{1}{\kappa_2}\right) - \left(\frac{\kappa_2}{\kappa_1}+\frac{\kappa_1}{\kappa_2}\right)\right\} \equiv -U_0$$

To exclude the δ-function from (8) we will make averaging over primary momentum of the electron-positron beams.

$$\frac{1}{\Delta(p_+ + p_-)_z}\int\delta\left[(p_+ + p_-)_z - k_z - k_{zs}\right]d(p_+ + p_-)_z, \quad (9)$$

where θ_m is the maximum angle deflection of electron and positron momentum from the z axis of the beamline. For estimations we will use the relation $\theta^2_m=\varepsilon^2_n/\gamma^2 s$ where ε_n is normalized emittance of electron (positron) beam. Other integrations are trivial. As a result we obtain

$$W_{if} = \{-U_0\}\frac{2\pi e^4 I_s}{16\omega\omega_s^2 E_+E_- Vs}\frac{k_z}{\omega}\frac{1}{2|p_+|\theta^2_{max}} \qquad (10)$$

For numerical estimations of the annihilation process while one positron is crossing the interaction region the formulae for the total probability in conventional units is:

$$P = \pi^3 r_0^2 \frac{I_s n_- c^2}{E_+\gamma^2\omega_s^3 s}\frac{1}{\varepsilon_n^2}, \qquad (11)$$

where $r_0 = 2.82\ 10^{-13}$ cm, n_- is number of electron in the interaction region.

Let us consider one example with the parameters:

$\gamma = 8.3\ 10^5$, $\lambda_o = 10^{-4}$ cm, $I_s = 10^{19}$ W/cm^2, $n_- = 10^{13}$,

$\varepsilon_n = 1\pi$ mm mrad for demonstration. From (11) it follows that the annihilation probability is $P = 2\ 10^{-6}$. It means that γ-beam will have six orders lower intensity than the positron beam.

The output is very low. At the same time stimulated gain is very high, $|A|^2 = 10^{24}$. The reason why it is not sufficient to achieve higher γ-beam intensities can be explained as very small phase space of particles satisfying the above kinematics. It limits the total cross-section of the stimulated process as well as energy and angular spreads of the γ-beam. They are defined actually by the respective energy and angular distributions of e -beam and laser photon beams.

In principle there are some potential ways to increase the output. The trivial one is to get higher beam intensities. Photon beam can be produced by high energy electron beam itself through free electron laser devices. Kinematic restrictions can be lowered for a different beam geometry where stimulating laser beam is directed at small angles but exceeding $\theta\sim1/\gamma$ with respect the e-beam axis instead of $\theta=\pi$ as was above supposed. In this short report we would like only to draw attention to the fact that very high enhancement of the annihilation process within small phase space is possible and can be used for future γ-γ colliders schemes of high energy and very high spectral luminosity.

ACKNOWLEDGMENTS

The author wishes to thank A. Hairetdinov and T. Yarovoi for their assistance with computer simulations.

REFERENCES

[1] P.R.Arutunian, V.A.Tumanian Phys.Rev.Lett. 4 (1963) 176.

[2] I.F.Ginsburg, G.L.Kotkin, V.G.Serbo, V.Telnov Pis'ma JETP 34 (1981) 514, in Russian.

[3] E.L.Saldin , V.P.Samartsev, E.A.Shneidmiller, M.V.Yurkov Nucl.Insrt.Meth A341(1994) ABS78

[4] Proceedings of the Workshop on gamma-gamma colliders. March 28-31, 1994. Bercly, CA, USA

[5] D.L.Borden, D.A.Bauer D.O.Caldwell. Preprint SLAC-PUB 5715, UCSB-HEP-92-01

[6] E.L.Saldin, V.P.Samartsev, E.A.Schneidmiller, M.V.Yurkov. Preprint of the Joint Inst. for Nucl.Res. E9-93-254, Dubna, 1993.

[7] A.A.Varfolomeev, V.N.Tikhonov Nucl.Instr.Meth. A331 (1993) 601

[8] A.I. Ahiezer, V.B. Berestetski "Quantum electrodynamics". Nauka, M., 1969, in Russian