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V.I. Telnov

SCATTERING OF ELECTRONS ON THERMAL RADIATION PHOTONS IN ELECTRON-POSITRON STORAGE RINGS

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НОВОСИБИРСК

Scattering of Electrons
on Thermal Radiation Photons
in Electron-Positron Storage Rings

V.I. Telnov

Institute of Nuclear Physics
630090, Novosibirsk, USSR

ABSTRACT

It is shown that Compton scattering on thermal radiation photons restricts a lifetime of high energy electron beams in storage rings at a level of 30 hours. At a vacuum pressure of 10^{-10} Torr a probability that an electron is knocked out from the beam due to scattering on thermal photons exceeds the probability of bremsstrahlung process on a residual gas ($\Delta E/E > 1\%$) by one order of magnitude, i. e. this effect can cause a considerable background in detectors.

1. INTRODUCTION

It is well known that in a Compton scattering of a low energy photon on a relativistic electron an energy of photon increases considerably. Feenberg and Primakoff [1] considered a process of energy loss of cosmic high energy electrons due to collisions with the radiation of the sun and stars. Soon after discovery of the relic thermal radiation the Compton effect on relic photons was considered as well [2]. It was shown that this effect restricts the range of cosmic electrons. In earthly laboratories the Compton scattering is used for obtaining high energy photons by backward scattering of laser photons on the high energy electrons [3, 4].

In this paper attention is drawn to the fact that at the modern high energy storage ring, especially at LEP, the collisions of electrons with the thermal photons must be taken into account. In the Compton scattering the electron can lose a sufficient amount of its energy ($\gtrsim 1\%$) for leaving the beam. This restricts the beam lifetime at the level of 30 hours ($T = 300$ K). Near experimental areas, where the vacuum pressure is usualy much higher than the average one, the bremsstrahlung radiation on a residual gas is suppressed and this process can account for a considerable part of the background in the detector.

2. KINEMATICS OF SCATTERING

Below some useful formulae for the Compton effect are presented [4]. It is convenient to use the dimensionless parameter

$$x=\frac{4E\omega_0}{m_e^2c^4}\cos^2\frac{\alpha_0}{2}, \qquad (1)$$

where E and ω_0 are primary energies of the electron and photon, α_0 is collision angle (see Fig. 1).

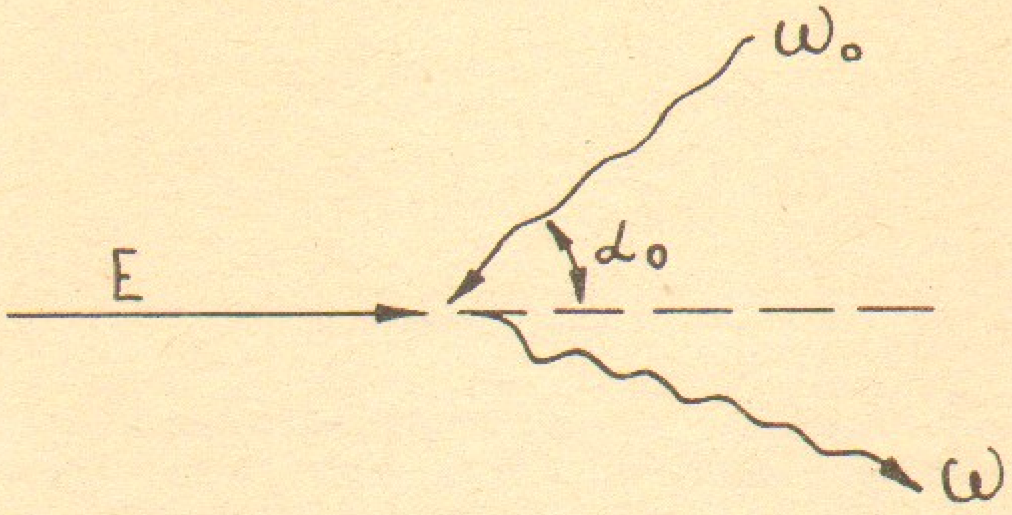

Fig. 1. Kinematics of the Compton scattering.

The total Compton cross section is

$$\sigma_C=\frac{2\pi r_e^2}{x}\left[\left(1-\frac{4}{x}-\frac{8}{x^2}\right)\ln(x+1)+\frac{1}{2}+\frac{8}{x}-\frac{1}{2(x+1)^2}\right], \qquad (2)$$

where $r_e=e^2/m_ec^2$. For $x\ll1$

$$\sigma_C=\frac{8\pi r_e^2}{3}(1-x), \qquad (3)$$

where the first term is the Tomson cross section

$$\sigma_T=6.65\cdot10^{-25}\ cm^2.$$

The energy spectrum of the scattered photons is defined by the cross section

$$\frac{d\sigma_C}{dy}=\frac{2\pi r_e^2}{x}\left[\frac{1}{1-y}+1-y-\frac{4y}{x(1-y)}+\frac{4y^2}{x^2(1-y)^2}\right], \qquad (4)$$

where $y=\omega/E$.

The maximum energy of the scattered photon corresponding to the case of the backward scattering is

$$\omega_m=\frac{x}{x+1}E. \qquad (5)$$

For $x\ll1$

$$\omega_m=xE=4\gamma^2\omega_0. \qquad (5')$$

The formula (4) is valid under condition $\pi-\alpha_0\gg1/\gamma$. If it is used for isotropic angular distribution of the thermal radiation photons the error will be small.

The density and energy distribution of the thermal photons is given by the Plank formula

$$dn_p=\frac{\omega_0^2\,d\omega_0}{\pi^2c^3\hbar^3\left(e^{\omega_0/kT}-1\right)}. \qquad (6)$$

The total number of photons in cm^3 is

$$n_p=\frac{2.4\,(kT)^3}{\pi^2c^3\hbar^3}=20.2\,T^3\ 1/cm^3. \qquad (7)$$

The average photon energy

$$\overline{\omega_0}=2.7\,kT. \qquad (8)$$

3. SPECTRUM OF SCATTERED PHOTONS AND BEAM LIFETIME

At $T=300$ K we have $n_p=5.45\cdot10^8$ cm^{-3} and $\overline{\omega_0}=0.07$ eV.For head-on collisions of electrons with the photons, having the energies $E=50$ GeV and $\omega_0=0.07$ eV, the parameter $x=0.055$ and a relative energy loss of the electron in the case of backward scattering will be $\Delta E/E=\omega/E=x/(x+1)=5\%$. Usually in storage rings the energy loss $\Delta E/E\sim1\%$ is enough to knock out the electron from the beam. For an estimation we can assume that all cases of Compton scattering lead to knock out of the electron and the cross section $\sigma_C=\sigma_T$ as soon as parameter x is small (see (2)). Then the average lifetime of electron can be estimated from the equation

$$n_p\sigma_Tc\,\overline{(1+\cos\alpha_0)}\,t=n_p\sigma_Tct=1. \qquad (9)$$

Here the factor $(1+\cos\alpha_0)$ arises due to a relative motion of electron and photon and is obtained from the formula for the invariant number of collisions [5]. For $T=300$ K we obtain from (9)

$$t=1./(5.45\cdot10^8\cdot6.65\cdot10^{-25}\cdot3\cdot10^{10})=92000\ \text{sec}\sim1\ \text{day}$$

For arbitrary E and T the energy distribution of scattered photons, produced by one electron passing 1 cm, is

$$\frac{dN}{dy}=c\int_0^{\pi}\int_{\omega_{min}}^{\infty}\frac{d\sigma_C}{dy}(1+\cos\alpha_0)\,dn_p(\omega_0,T)\frac{d\Omega}{4\pi}; \tag{10}$$

where $\omega_{min}=\frac{ym_e^2c^4}{4(1-y)E\cos^2(\alpha_0/2)}$, $\frac{d\sigma_C}{dy}$ is defined by formula (4) and when integrating one has to use the constraint (1).

The lifetime of particles in the beam is

$$t=\frac{1}{c}\left[\int_q^1\frac{dN}{dy}\right]^{-1} \tag{11}$$

where $q=\Delta E/E$ is a relative energy loss leading to knock-out of electron from the beam.

The integral in the formula (10) can not be taken analytically and calculations have been carried out by a Monte Carlo method. The normalized distributions over the energy of scattered photon or, what is the same, over the energy loss of the electron are shown in Fig. 2. The dashed curve in the same figure is a spectrum of the bremsstrahlung radiation on the residual gas (10^{-9} Torr of CO) under a proper normalization to the Compton spectra. This function is

$$f_{brems}=\frac{1.3\,n_g\mu}{n_p\overline{\sigma_C}N_0X_0}\frac{1}{y}. \tag{12}$$

where n_g—gas density (1/cm^3), μ—molecular weight (28 for CO), X_0—radiation length (37.5 g/cm^2 for CO), N_0—Avogadro number, $\overline{\sigma_C}=\overline{\sigma_C(1+\cos\alpha_0)}\approx\sigma_T$, factor 1.33 follows from the formula for the bremsstrahlung process at $y=\omega/E\ll 1$, n_p—density of thermal photons (7). For $E<100$ GeV and $T=300$ K the difference between $\overline{\sigma_C}$ and σ_T is less than 10% and then we get from (12)

$$f_{brems}\approx 0.15/y. \tag{12'}$$

One can see from Fig. 2 that in the certain energy regions the number of Compton photons exceeds the number of bremsstrahlung photons.

In Fig. 3 the beam lifetime is presented for different energies as a function of minimum energy loss $q=\Delta E/E$, at which electrons are

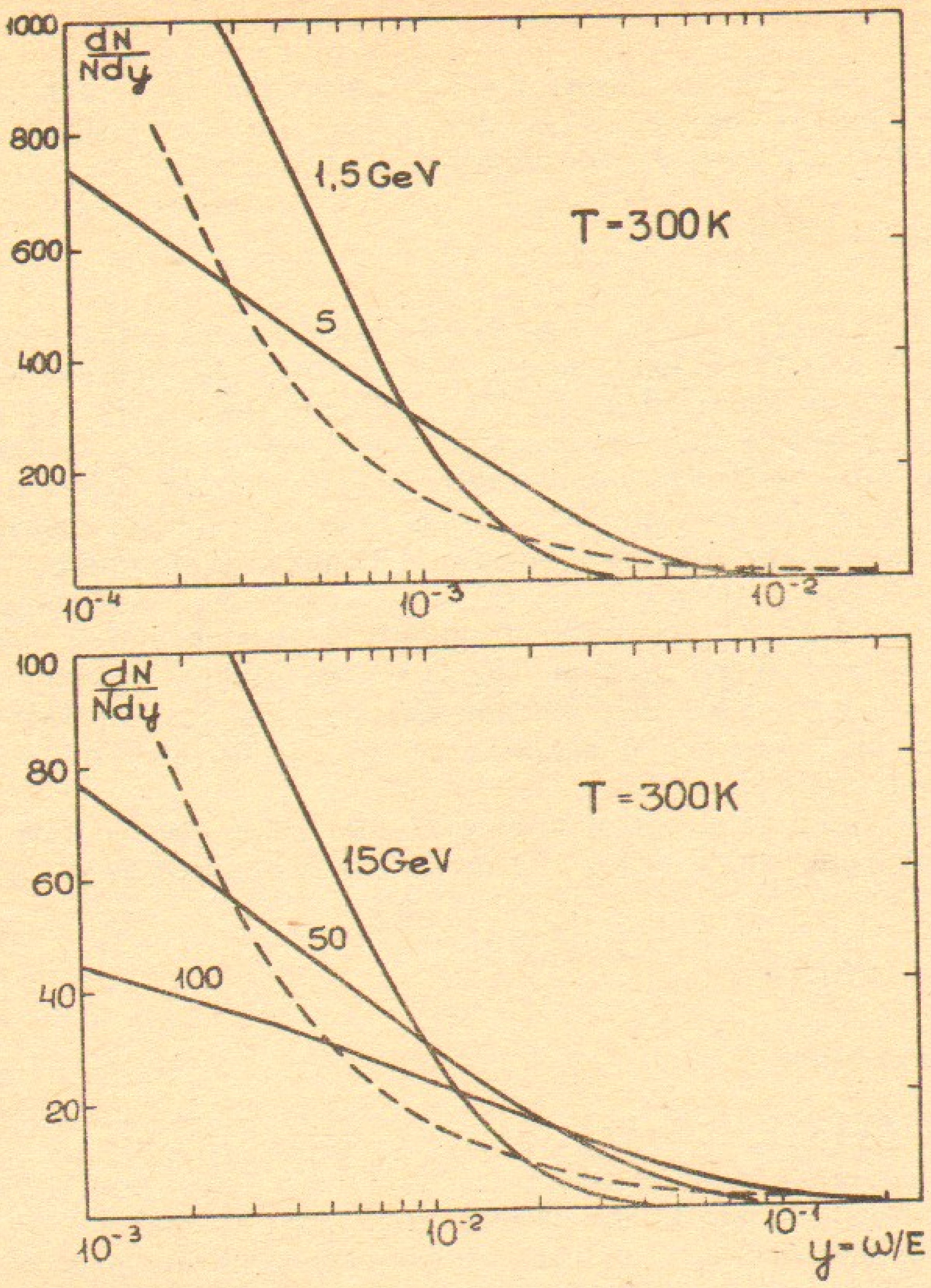

Fig. 2. Energy spectra of scattered photons (areas are normalized to unit). Numbers — energies of electrons (GeV); temperature of thermal radiation $T=300$ K. Dashed curve — spectrum of the bremsstrahlung radiation on the residual gas (10^{-9} Torr CO), normalized to the Compton spectra.

knocked out from the beam. By the dashed line the beam life is shown due to the bremsstrahlung process on the residual gas (10^{-9} Torr CO). For the considered case

$$t_{brems}(\text{hours}) \approx \frac{160}{\ln(1/q) - 0.65}. \tag{13}$$

In the LEP storage ring the average vacuum of the order $1.5 \cdot 10^{-9}$ Torr CO is expected [6], i. e. the beam lifetime due to residual gas is about 20 hours. The beam lifetime due to Compton scattering will be about 30 hours. However, the relative contribution of the latter effect is considerably larger near the experimental areas, where the vacuum 10^{-10} Torr is expected. In these places the probability of electron knock out due to Compton scattering on thermal radiation photons exceeds the same due to bremsstrahlung on the residual gas by one order of magnitude. It is clear that this effect will add background in detectors. The particle spectra from these two sources are different and relative increase of background depends on the particular magnetic system and the geometry of experimental area.

It is useful to note that until $x \ll 1$ the photon spectra have the same shape for all E and T if a variable y is replaced by $y' = y/ET$ one obtains:

$$\frac{dN}{dy'} \infty T^3 f(y'), \tag{14}$$

and for a beam lifetime

$$t \infty T^{-3} \varphi\left(\frac{q}{ET}\right). \tag{15}$$

This makes possible to use graphs in Fig. 3 for other cases. For LEP energies the beam lifetime depends mainly on the temperature. Perhaps, for decreasing the background it is reasonable to cool the vacuum chamber in certain places.

Recently Piwinski [7] has considered the mechanism of knock out of electrons from the beam due to Compton scattering of electrons by synchrotron radiation photons of the same beam. For LEP at the energy of 95 GeV the beam lifetime of 19 hours was obtained. Unfortunately some calculation in this work are erroneous. The correct value of the beam lifetime due to this effect is larger by 3 orders of magnitude.

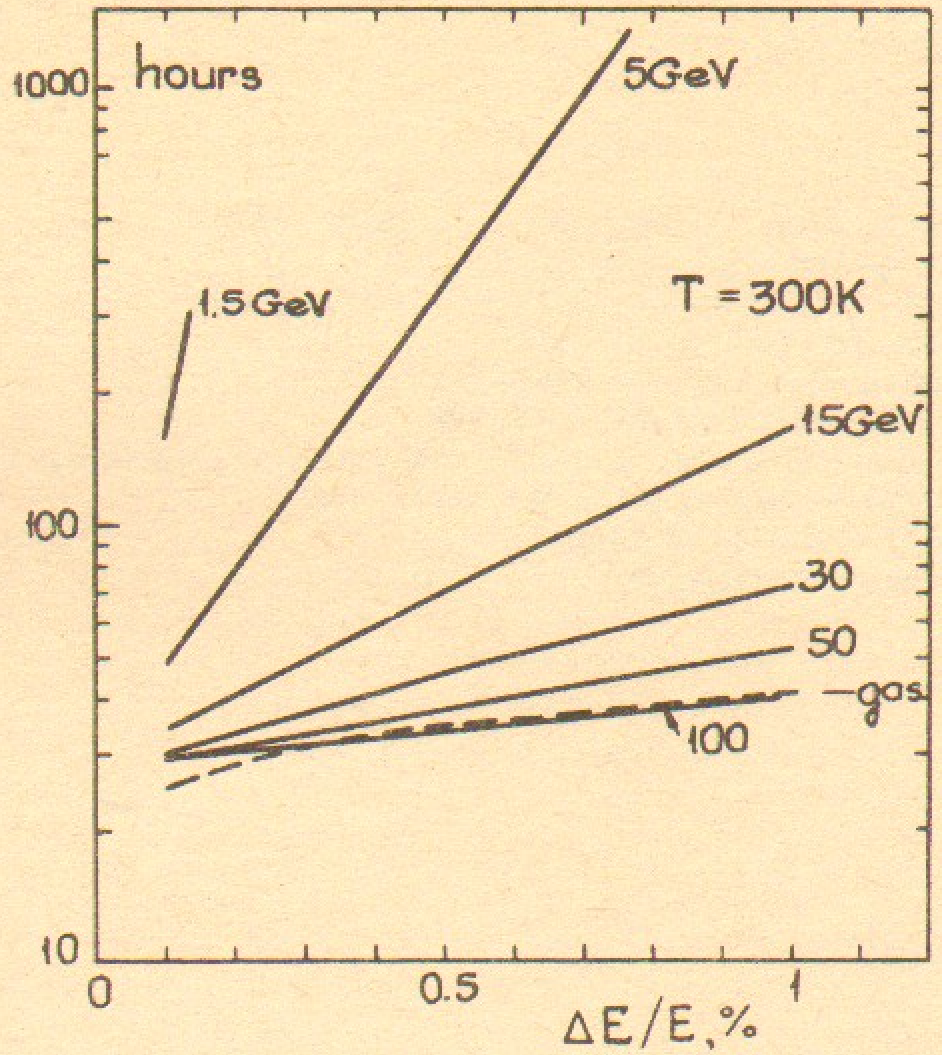

Fig. 3. Beam lifetime due to a Compton scattering on photons of thermal radiation vs. the minimum energy loss at which electrons leave the beam. Numbers give the electron energies (GeV); temperature of termal radiation $T = 300$ K. Dashed curve — beam lifetime due to bremsstrahlung radiation on residual gas (10^{-9} Torr CO).

In conclusion I would like to point out that Compton scattering on the thermal radiation photons can easily be observed at any existing electron-positron storage ring. This effect should be taken into account in the design of experimental areas.

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В.И. Тельнов

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