Beam Lifetimes in LEP

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Abstract

Single beam lifetimes in LEP are about 50 hours at 45 GeV beam energy. The dominating process is Compton scattering on thermal photons. The lifetime of colliding beams is reduced to typically 20 hours by the process of beam-beam bremsstrahlung. This agrees with calculations, provided that a cutoff parameter corresponding to an effective distance between the particles in the bunches is introduced.

1 INTRODUCTION

Beam lifetimes in LEP are about three times longer then originally anticipated [1]. To a large extend, this is due to the excellent vacuum conditions with average pressures of $\leq 10^{-10}$ Torr or beam-gas lifetimes of ≥ 200 hours. The observed lifetimes are mainly limited by two fundamental scattering processes :
i) Compton scattering on thermal photons
ii) e^+e^- scattering in case of colliding beams

2 SINGLE BEAM LIFETIMES AND SCATTERING ON THERMAL PHOTONS

The fact that the lifetime of high energy storage rings is affected by the scattering off the thermal photons radiated from the beam pipe was pointed out by Telnov in 1987 [2]. The energy spectrum of the scattered photons has been measured in LEP and found to be in agreement with the expectations [3]. The effect on beam lifetimes has also been discussed in [4] and [5]. The lifetime from scattering on thermal photons is :

$$\tau_{th} = \underbrace{\frac{1}{\rho_\gamma \, c \, \sigma_C}}_{26.2h} \cdot \frac{1}{f_{los}}$$

where ρ_γ ($5.329 \cdot 10^{14} m^{-3}$ for $T = 24°C$) is the density of photons, σ_C the Compton cross section (approximately equal to the Thomson cross section or 0.6652 barn) and f_{los} the fraction of the $e^\pm$ lost after collision. The average energy of the scattered photons is about 1.1 % of the beam energy at LEP1 and about 2.2 % at LEP2. The fraction of beam particles lost after collision with a thermal photons depends on the energy loss and the energy acceptance of the machine. A quantitative comparison between measured single beam lifetimes and the expectation from Compton scattering on thermal photons is given in table 1 for LEP at 45.6 GeV and two optics cases [6]. The synchrobetatron tune Q_s, momentum compaction factor and the calculated bucket (half) height used as energy cutoff in the calculation are also given in table 1. The difference between measurement and calculated lifetime from scattering on thermal photons corresponds to 100 ± 10 hours. About half of this can be explained by losses in beam gas scattering with an expected single beam lifetime contribution of about 200 hours. The other half is attributed to a reduction in energy aperture compared to the bucket height [7]. This was confirmed by tracking studies and comparison of single beam lifetimes under usual conditions (squeezed optics, tight collimators settings) and special conditions (unsqueezed beams, loose collimator settings).
No significant difference in the lifetimes of single or two separated beams was observed.

3 LOSSES IN COLLISION

For colliding beams, the event rate (here loss rate) is calculated according to

$$\dot{n} = n^+ n^- \, f \, \frac{\sigma}{A} = L \cdot \sigma$$

where n$^+$, n$^-$ are the number of particles per bunch and f the single turn frequency; σ is the total cross-section leading to the loss of a beam particle. From the overlap integral of two 2-dimensional gaussians we get the effective area $A = 4\pi\sigma_x\sigma_y$. The beam-beam lifetime is

$$\frac{1}{\tau_+} = \frac{x}{n^+}\frac{dn^+}{dt} = \frac{x \; e \; f}{i_b}\frac{dn^+}{dt} = \frac{L}{I^+}\sigma \; x \; e \; f$$

where a factor x for the number of crossing points (4 in the case of LEP) has been taken into account. L is the luminosity seen by each experiment from the sum of k bunches (k=4 or 8 in LEP). The total beam current is $I = k \; i_b$. The bunch current is related to the number of particles per bunch and the single turn frequency according to $i_b = n \; e \; f$. The equivalent lifetime formula can be written for the e^- beam. For equal beams and running at a constant beam-beam limit we have the following proportionalities:

$$\frac{1}{\tau} \propto \frac{L}{I} \propto \xi_y = \text{constant}$$

leading to exponential decay of the currents with:

$$I = I_0 \, e^{-t/\tau}$$

phase advance hor./vert.	Q_s	momentum compaction	bucket height %	f_{los} %	τ thermal [h]	τ seen [h]
60/60°	0.085	$3.867 \cdot 10^{-4}$	0.78	43.8	61.2	39 ± 1
90/60°	0.0625	$1.859 \cdot 10^{-4}$	1.28	30.6	87.5	48 ± 2

Table 1: Calculated single beam lifetime from scattering on thermal photons and measured single beam lifetimes at LEP at 45.6 GeV for two optics configurations

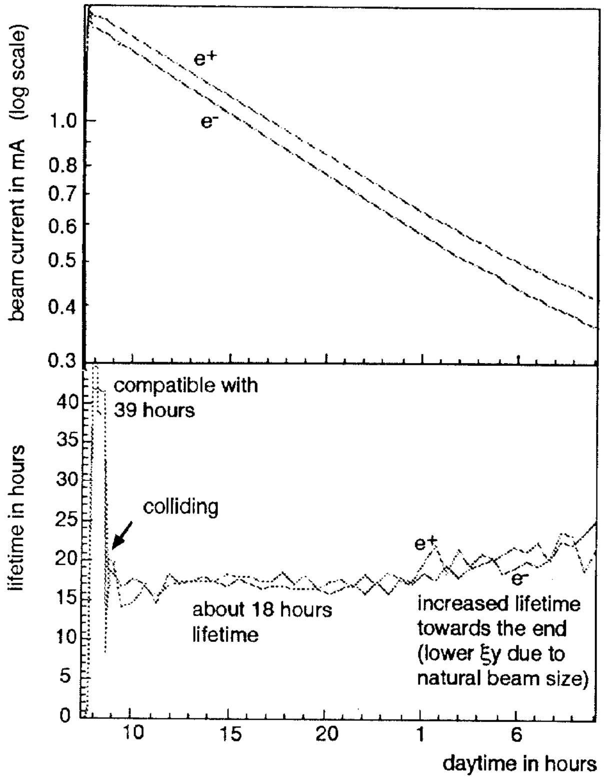

Figure 1: Current and lifetime during a 27 hour coast of LEP

Using the standard formulas for the luminosity in the beam-beam limit with flat beams ($\sigma_x \gg \sigma_y$) we get:

$$\tau_b = \frac{2 r_e m_e}{x\ f\ \sigma} \frac{\beta_y^*}{E_b\ \xi_y}$$

The evolution of currents and lifetimes is illustrated in figure 1 for a long coast (kept for 27 hours in LEP due to problems in the injectors). During the last hours of the coast, the luminosity was not any more beam-beam limited. L/I decreased, leading to an increase in beam-beam lifetime. Figure 2 demonstrates the proportionality between L/I and the inverse beam-beam lifetime for the same coast. After some additional (transverse) losses during the first hours, the e^+, e^- beam lifetimes followed L/I. The proportionality can be used to determine the total e^+e^- cross-section, leading to beam-particle loss. The result is shown in figure 3. The cross-section is obtained using a gauss-fit restricted to the central region of the histogram. This is done to avoid a bias towards shorter lifetimes from occasional additional losses. Using the data of many fills

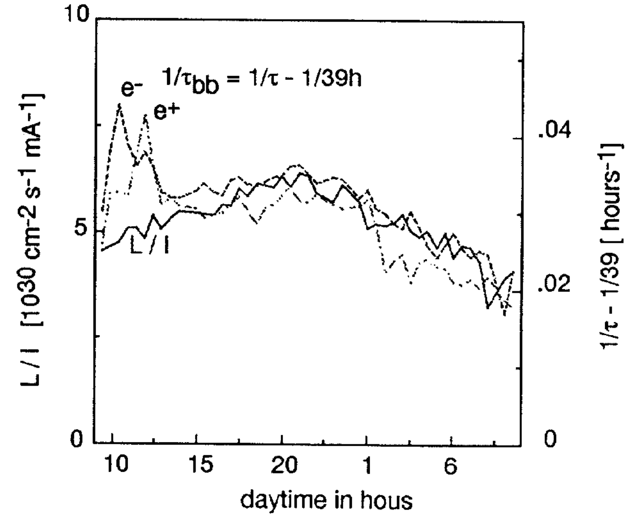

Figure 2: L/I and inverse beam-beam lifetime in a 27 hour coast of LEP

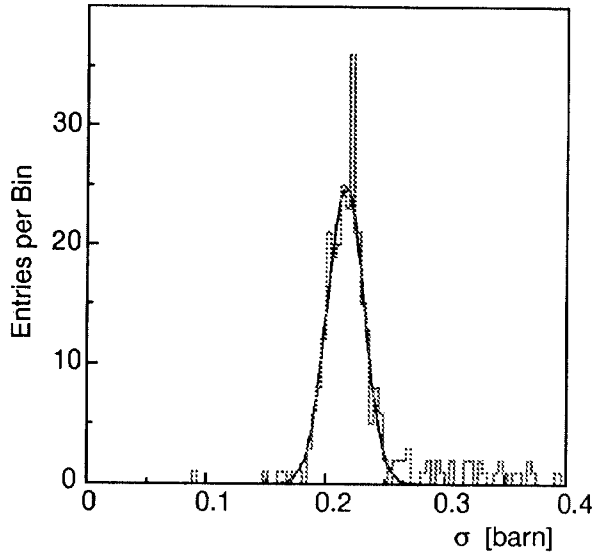

Figure 3: Total cross-section obtained from the beam-beam lifetime

and the luminosity of all four experiments, the measured cross-section is $\sigma = 0.21 \pm 0.02$ barn.

4 STANDARD CROSS SECTION

The relevant process for beam lifetimes is beam-beam bremsstrahlung (radiative Bhabha scattering, dominated by the t-channel and initial state γ-radiation at ≈ 0 angle) [8]:

$$\frac{d\sigma}{dk} = \frac{4r_e^2\alpha}{k}\left[\frac{4}{3} - \frac{4}{3}k + k^2\right]\left[\log(4\gamma_e^+\gamma_e^-) + \log\frac{1-k}{k} - \frac{1}{2}\right]$$

k is the fractional photon energy ($k = E_\gamma/E_b$). The loss is concentrated on one beam particle and therefore equal to the photon energy. It is interesting to note, that the cross-section is dominated by the Coulomb term, and the result therefore equivalent to electron-proton bremsstrahlung. The beam particles are lost when the energy loss exceeds the energy acceptance. The scattering angle of the e^+ or e^- after radiation of a photon with fractional energy k is typically very small compared to the beam-divergence at the IP. The beam-bremsstrahlungs losses are therefore obtained in very good approximation by integration over all angles and energy losses from photon energies equal to the energy aperture (≈ 1 %) up to the maximum kinematically allowed ($k_{max} \approx 1$):

$$\sigma = \int_{k_{min}}^{k_{max}} \frac{d\sigma}{dk} \approx 0.32 \text{ barn}$$

The result depends only weakly (logarithmically) on the minimum photon energy and does therefore not require a precise knowledge of the energy aperture. The significant discrepancy between measured and calculated cross sections was presented in [9] and attributed to an effective screening of the Coulomb fields in dense bunches. Later we learned that a reduced cross section had been observed earlier at Novosibirsk and attributed to a cutoff parameter derived from the transverse beam dimensions [10]. We do not agree with that explanation, that for example fails to reproduce the single particle case were rms beam sizes vanish. Our main ideas and results are shortly summarized in the following chapter.

5 INTRODUCTION OF A CUTOFF PARAMETER

The effective overlap area of gaussian bunches for luminosity (collisions) is $F = 4\pi\sigma_x\sigma_y$. Extended to three dimensions, this leads to the effective volume $V = (4\pi)^{3/2}\sigma_x\sigma_y\sigma_z$ or in the rest system $V^* = (4\pi)^{3/2}\sigma_x\sigma_y\gamma\sigma_z$. In the beam-beam limit, the transverse beam dimensions are proportional to the beam-beam tuneshift parameter ξ_y such that

$$\rho^* = \frac{\xi_y}{2\sqrt{4\pi}r_e\beta_y^*\sigma_z}$$

or numerically $\rho^* = 3.5 \cdot 10^{15}\ m^{-3}$ for current LEP parameters and $\xi_y = 0.03$. The length of a cube, that contains in average only one particle is $\rho*^{-1/3}$. The Coulomb force vanishes halfway between two particles, at a distance of $d = 1/2 \cdot \rho*^{-1/3} \approx 3.3 \cdot 10^{-6} m$ for LEP I. This distance corresponds to a momentum-transfer squared of $(\hbar c/d)^2 = 3.56 \cdot 10^{-21}$ GeV^2. We developed a Monte Carlo simulation program for the process of beam-beam bremsstrahlung[11]. Cuts can be imposed on an event by event basis. The introduction of a cutoff in the momentum transfer corresponding to a distance of 3.3 μm results in a significant reduction of the cross section, particularly at high beam energies, as can be seen from table 2. The predicted cross section including the cutoff agrees well with the observation.

E_b GeV	no cutoff barn	cutoff barn
0.51	0.2081	0.1987
30	0.3086	0.2102
45.6	0.3189	0.2101
95	0.3368	0.2098

Table 2: Calculated beam-beam bremsstrahlung cross section with and without cutoff at 3.3 μm for various beam energies assuming a minimum photon energy (energy acceptance) of 1 %.

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