# Beam Lifetime and Beam Tails in LEP

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**Abstract**

Measurements of beam lifetime and non-Gaussian beam tails in LEP will be summarized. The measured beam lifetimes are compared to the lifetime expected from scattering processes. Non-Gaussian beam tails have been observed for colliding beams and on a much lower but still significant level also for single beams. The quantum lifetime was measured and compared with predictions.*

# 1 Lifetime

In stable running conditions, beam lifetimes in LEP can be accounted for by inelastic particle scattering processes [1]:

- Compton scattering on black-body photons
- beam-gas bremsstrahlung
- $e^+e^-$ collisions, dominated by beam-beam bremsstrahlung (very small angle radiative Bhabha scattering)

The scattering angles for these processes are quite negligible at LEP energies: of the order of $1/\gamma$ which is $11\,\mu$rad at LEP1 ($45.6\,$GeV) and $5.4\,\mu$rad at LEP2 ($94.5\,$GeV). The scattered particles are rather lost if their energy deviation $\Delta E/E$ exceeds the energy acceptance (the bucket-half-height, in LEP typically $1.4\,\%$).

This will now be further illustrated and quantitatively analyzed for a particular fill in LEP (fill 5259 with the highest luminosity and beam-beam tune shift in 1998).

Fig. 1 shows the evolution of beam currents and luminosity with time for this fill. The loss rate or inverse lifetime $1/\tau$ is obtained from the relative change of beam currents $\Delta I/I$ with time according to:

$$\frac{1}{\tau} = \frac{1}{\Delta t} \cdot \frac{\Delta I}{I}$$

Losses from different loss mechanisms have to be added. This implies, that the corresponding lifetime contributions add reciprocally:

$$\frac{1}{\tau} = \sum_i \frac{1}{\tau_i}$$

The luminosity shown in Fig. 1 was obtained as average of the luminosity of the four LEP experiments for time intervals of 15 minutes. The LEP experiments use low angle Bhabha scattering, corrected for dead-time in the read-out system, to monitor the luminosity on-line. Both the beam-current/lifetime and luminosity data shown in the Figure are expected to be precise to a few percent.

Before beams were brought into collisions, the observed lifetime was $\tau_s = 34\,$h.

The lifetime expected from Compton scattering on thermal photons is $\tau_c = 60\,$h. This was determined by Monte Carlo simulation [2] for the relevant beam parameters (beam energy $E_b = 94.5\,$GeV and energy acceptance $s_b = 1.4\,\%$). The remaining $80\,$h are compatible with beam-gas scattering for a mean pressure of $0.6\,$ntorr.

The lifetime dropped from $34\,$h to $5.0\,$h when the beams where brought into collisions.

The expected lifetime from collisions in $n_c$ interaction regions is [3]:

$$\tau_b = \frac{2\,r_e\,m_e\,c^2}{n_c\,f_0\,\sigma_b}\,\frac{\beta_y^*}{E_b\,\xi_y} \tag{1}$$
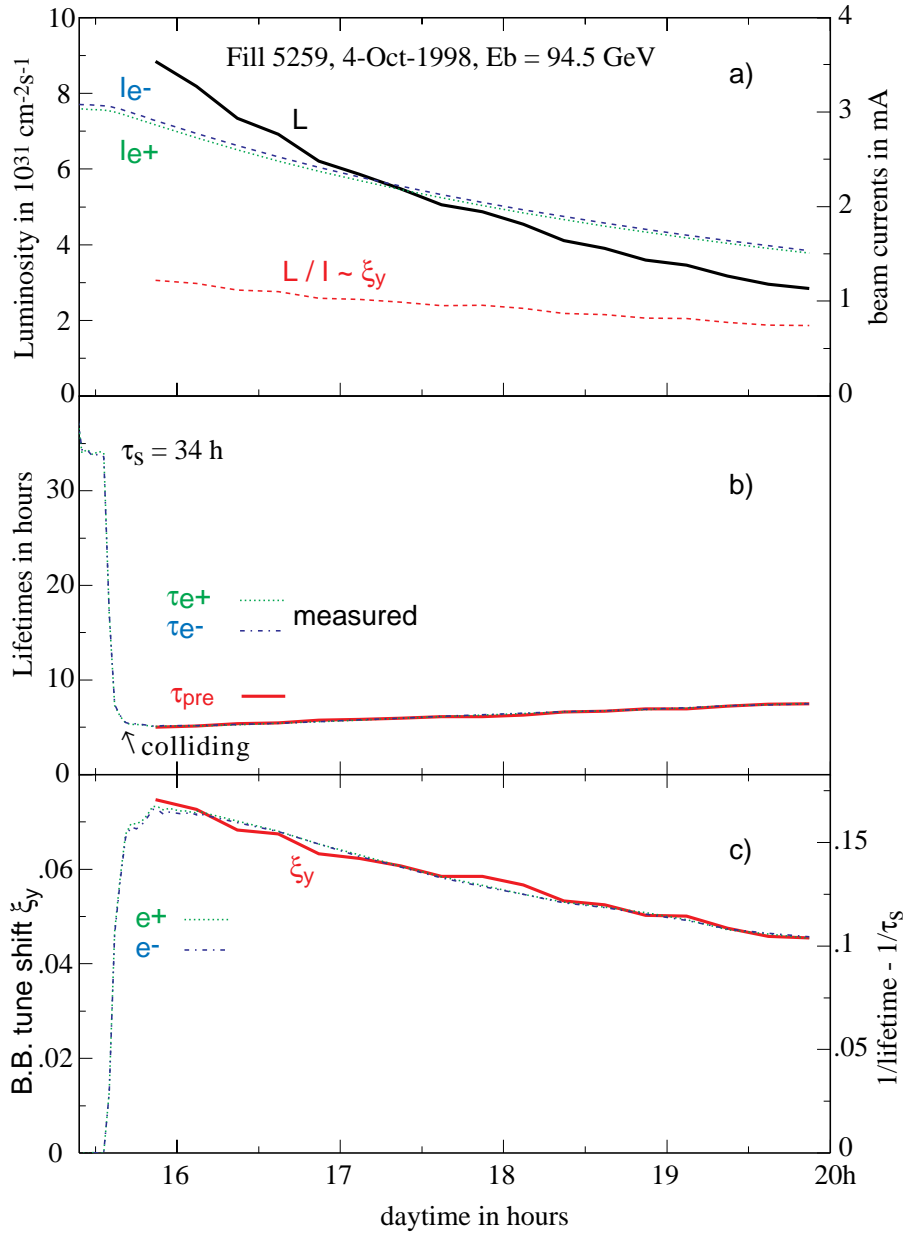
Figure 1: Evolution of beam parameters with time for fill 5259. a) Luminosity $L$ and beam currents $I$. The ratio $L/I$ is also shown and proportional to the beam-beam tune shift $\xi_y$. b) Observed positron $\tau_e^+$ and electron $\tau_e^-$ lifetimes and the predicted lifetime in collisions $\tau_{pre}$. The lifetime drops from $\tau_s \approx 34\,\mathrm{h}$ to about $5\,\mathrm{h}$ when beams are brought into collision. c) The vertical beam-beam tune shift parameter $\xi_y$ and the inverse lifetime (single beam lifetime subtracted)

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Table 1: Contributions to the total lifetime, beginning of fill 5259

| process | lifetime |
|---|---|
| Compton thermal photon | $\tau_t = 60\,\mathrm{h}$ |
| beam gas, $0.6\,\mathrm{ntorr}$ | $\tau_g = 80\,\mathrm{h}$ |
| total, single beam | $\tau_s = 34\,\mathrm{h}$ |
| collisions, rad. Bhabha | $\tau_b = 5.8\,\mathrm{h}$ |
| total, colliding beams, $\xi_y = .075$ | $\tau = 5.0\,\mathrm{h}$ |

where $f_0$ is the revolution frequency and $m_e$, $r_e$ the electron mass and classical radius. The cross section from very low angle Bhabha scattering, taking into account that the particles are confined to bunches, can be determined using the program of [4]. For the parameters of fill 5259 the cross section is $\sigma_b = 0.215\,\mathrm{barn}$. Putting in values for all constants, we obtain for Eq. (1):

$$\tau_b = \frac{0.44\,\mathrm{h}}{\xi_y}$$

The proportionality between $\xi_y$ and the inverse lifetime in collisions can be seen in Fig. 1 c.

The total lifetime as predicted from the three contributions discussed here is shown in Fig. 1 b and agrees very well with the observed lifetimes. The lifetime contributions are also summarized in Tab. 1.

## 2    Beam Tails

Additional losses, not accounted for by scattering processes, were occasionally seen at high currents and beam-beam tune shifts. They are attributed to scraping of non-Gaussian tails. The drops in lifetime generally coincided with background spikes observed in the experiments. In such occasions, very small changes in betatron tune (.005 or less) could often make the problem much worse or virtually disappear.

While the overall background level from synchrotron radiation increased as expected, it was interesting (and encouraging for future high energy e$^+$e$^-$ colliders, see [5]) to see that the probability for background spikes decreased in going from LEP1 to LEP2 energies. Much higher currents could be put safely into collision and stable operation with very high beam-beam tune shift parameters became possible.

Non-Gaussian tails have been studied quantitatively in LEP using scrapers and loss monitors [6]. At a very low level, they are already present for single beam and can be explained by the same scattering processes that are responsible for the beam lifetime in LEP [7].

Beam tail measurements have also been used in LEP as a tool to map out the available aperture [8, 9].

Tail scans showed that the amount of non-Gaussian tails can increase significantly for high currents and high beam-beam tune shifts. High chromaticities can further

enhance tails [10].

# 3   Quantum lifetime

The quantum lifetime $\tau_q$ is a steep function of

$$n_\sigma = s_b/\sigma_e = \frac{\text{relative bucket height}}{\text{relative energy spread}}$$

To be stable even in the case of a trip of an rf-unit, LEP usually runs with sufficient overvoltage such that the quantum lifetime is very long compared to the lifetime from scattering processes discussed before.

According to Sands [11, 12], the quantum lifetime is given by:

$$\tau_q = \frac{\tau_e}{n_\sigma^2} \exp\left(\frac{n_\sigma^2}{2}\right) \tag{2}$$

Several theoretical discussions of the quantum lifetime can be found in the literature [13, 14]. F. Ruggiero suggested a different treatment close to the bucket boundary, based on Kramers and Chandrasekhar [15, 16] and obtained [17]:

$$\tau_q = \frac{1}{f_0\, Q_s} \exp\left(\frac{n_\sigma^2}{2}\right) \tag{3}$$

For LEP this results in lifetimes longer by about a factor of 10 or in about 1 % less rf-voltage needed for the same lifetime. Numerical values (at 90 GeV and for a longitudinal damping time of $\tau_e = 4.2$ ms are):

| $n_\sigma =$ $s_b/\sigma_e$ | $n_\sigma^2 / 2$ | Sands $\tau_q$, [h] | Ruggiero $\tau_q$, [h] | $Q_s$ | $V_{RF}$ MV |
|---|---|---|---|---|---|
| 5 | 12.5 | 0.01 | 0.07 | .0902 | 2075 |
| 5.5 | 15.125 | .15 | 1 | .0934 | 2097 |
| 6 | 18 | 2 | 17 | .0963 | 2119 |
| 6.5 | 21.125 | 40 | 400 | .0991 | 2144 |
| 7 | 24.5 | 1000 | 10000 | .1018 | 2167 |

A list of many small, often neglected effects influencing the quantum lifetime is discussed in [18]. The main effect in LEP2 is about equivalent to a gain in voltage of 40 MeV or 2 % of the total voltage and can roughly be explained as follows: The energy acceptance or bucket-height is usually calculated using the nominal beam energy and energy loss and found to be symmetric for positive and negative energy deviations. This is only approximately true. The quantum lifetime depends on particles close to the lower boundary of the rf-bucket. These particles have about 1.4% less than nominal energy and in consequence radiate less energy and are more effectively focused by the rf-voltage. This effect has been checked by simulation [18].

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Experimentally, it is not too difficult to measure the quantum lifetime in a machine. The rf-voltage is lowered, until the lifetime becomes very short – the total lifetime is then completely dominated by the quantum lifetime. The challenge is rather the precise knowledge of all relevant machine parameters. Fortunately, some of theses are rather directly and precisely measurable: the total energy loss and the absolute rf-voltage calibration can be determined accurately from a measurements of the synchrotron tune $Q_s$ as function of the rf-voltage [19].
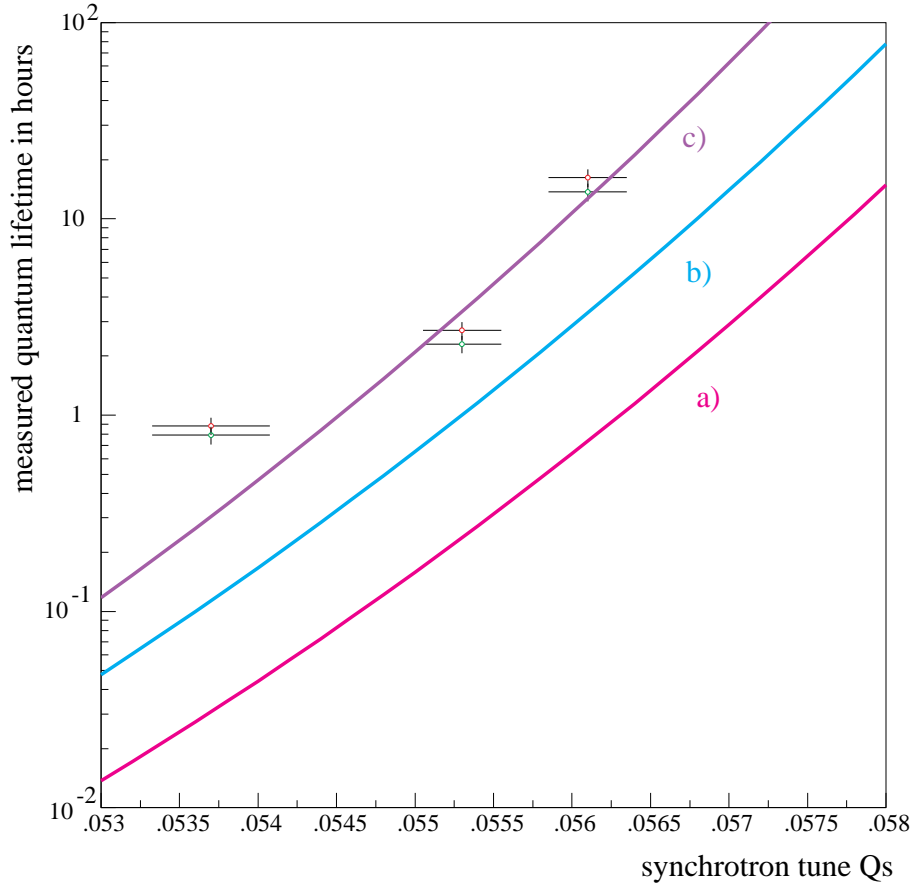


Figure 2: Measured (crosses with error bars for $e^+$ and $e^-$ particles) and the predicted quantum lifetime in LEP (solid lines). The curve labelled a) is obtained from the Sands formula Eq. (2). Curve b) is based on Ruggiero's expression Eq. (3). For curve c), the reduced synchrotron radiation at the lower rf-bucket boundary was taken into account as proposed in [18].

A measurement of the quantum lifetime in LEP and a comparison with predictions is shown in Fig. 2. The beam energy was $E_b = 66.046 \, \text{GeV}$ (LEP fill 5128 on the 4/9/1998). The total energy loss and rf-calibration were determined in the same fill and found to be very close to the prediction.

The largest experimental uncertainty is expected to come from the knowledge of

the momentum compaction factor. The difference between curves a) and c) corresponds to a change of the momentum compaction factor $\alpha_c$ by about 2 %. In LEP, $\alpha_c$ should be known to 1 % or better (it was measured for the polarization optics and found to be in very good agreement with the expectation).

## 4  Summary and conclusion

Lifetimes in LEP can well be accounted for by three inelastic scattering processes: Compton scattering on black body photons, bremsstrahlung in beam-gas scattering and the beam-beam bremsstrahlung in the $e^+e^-$ collisions.

Non-Gaussian tails have been measured. They are always present at low level as expected from scattering processes. They can strongly be enhanced for colliding beams at high currents and beam-beam tune shifts.

The quantum lifetime was measured and found to be somewhat longer than expected for nominal parameters. The agreement with nominal parameters instead is excellent, when the reduction in synchrotron radiation for particles close to the lower bucket boundary is taken into account.

## 5  Appendix

The total energy loss in synchrotron radiation $U_0$, the synchrotron tune $Q_s$, the fractional energy spread $\sigma_e$, the stable phase angle $\phi_s$ and the bucket (half) height can be written as:

$$U_0 = c_\gamma E_b^4 \left\langle |1/\rho| \right\rangle = e\, V_{RF}\, \sin\phi_s$$

$$Q_s^2 = \frac{\alpha_c h}{2\pi E_b} \sqrt{e^2\, V_{RF}^2 - U_0^2} = \frac{\alpha_c h\, U_0}{2\pi E_b\, |\tan\phi_s|}$$

$$\sigma_e = \gamma\, \sqrt{\frac{c_\gamma\, I_3}{J_e\, I_2}} = \gamma \sqrt{\frac{c_\gamma \langle |1/\rho^3| \rangle}{J_e\, \langle |1/\rho^2| \rangle}}$$

$$s_b = \sqrt{\frac{2U_0}{\pi \alpha_c h E_b} \left( \frac{\pi}{2} - \phi_s - \mathrm{ctg}\,\phi_s \right)}$$

$E_b$ is the beam energy, $h$ the harmonic number, $\alpha_c$ the momentum compaction, $J_e$ the longitudinal damping partition number, $I_2$ and $I_3$ the standard synchrotron radiation integrals, $\rho$ the local bending radius, $\gamma$ the Lorentz factor, $c_\gamma = 55\,\hbar c/32\sqrt{3} m_e c^2 = 3.832 \cdot 10^{-13}$ m and $< .. >$ indicate averages around the machine.

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