

Beam Lifetime and Beam-Beam Tails in LEP

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1 Introduction

LEP is currently running in its 6th year at Z-energies with beam energies of about 45.6 GeV. Single beam emittances can be rather small. About $\varepsilon_x = 12$ nm in the horizontal plane and still 2 orders of magnitude less in the vertical plane. Single beam lifetimes are about 40-50 hours and mainly limited by Compton scattering with black body radiation.

In collisions, beam sizes increase significantly in both planes as result of the beam-beam interaction. Lifetimes are reduced to about 17 hours due to "loss" of particles in e^+e^- collisions. Beam-beam tunes in excess of 0.04 have been reached routinely in operation [1]. Significant beam-beam tails are observed for high beam-beam tunes and bunch currents. They limit the maximum current that can safely be collided [2].

2 Standard Operation

LEP is filled at 20 GeV beam energy via a sequence of accelerators (the dedicated LIL and EPA and the PS and SPS as pre-accelerators). Currents of about 350 μ A per bunch corresponding to $2 \cdot 10^{11}$ particles are accumulated in a couple of minutes. LEP was operated 1993 and 1994 with 8+8 bunches in the horizontal Pretzel scheme[3]. The number of bunches can be doubled this year using bunch trains with vertical separation.

Ramping the beam energy E_b from 20 to 45.6 GeV beam energy takes 6.5 minutes. Beams are then squeezed vertically to $\beta_y^* = 5$ cm in one minute. The horizontal β_x^* is kept constant at 2.5 m. Pre-collision tunes in LEP are set to $Q_x = 90.3$ and $Q_y = 76.2$.

For flat beams ($\varepsilon_x \gg \varepsilon_y$) with $n = 2 \cdot 10^{11}$ particles, a Lorentzfactor $\gamma = E_b/m_e = 89237$, the horizontal beam-beam tunes becomes (r_e is the classical electron radius):

$$\xi_x = \frac{r_e n}{2\pi \gamma \varepsilon_x} \approx \frac{1 \text{ nm}}{\varepsilon_x} \quad (1)$$

The horizontal single beam emittance is increased from $\varepsilon_x = 12$ to 36 nm using a wiggler in a region of horizontal dispersion (the "emittance wiggler") to bring beams safely into collision. This assures that ξ_x cannot exceed the value given by equation(1) (or a value of 0.028 for 350 μ A per bunch) and proved to be very effective to avoid flip-flop and excessive beam-beam tails with background and lifetime problems.

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3 Beam Lifetimes, example of LEP fill 2420

Fig. 1 illustrates the evolution of luminosity and currents in a recent LEP coast. About 2.6 mA per beam or 320 μA per bunch were brought into collision. The positron current was about 7 % higher than the electron current. The ratio luminosity to beam current (L/I) is directly proportional to the

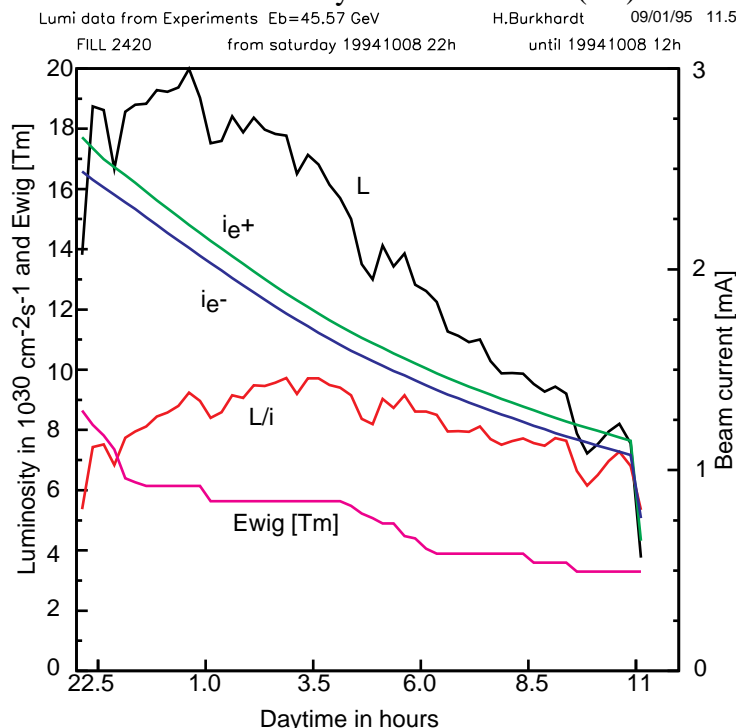


Figure 1: Evolution of Luminosity and Currents in Fill 2420. The setting of the emittance wiggler (Ewig) is also shown.

vertical beam-beam tune shift parameter ξ_y and tends to be about constant during coasts. In this fill, ξ_y quickly exceeded values of 0.04 with peak values up to 0.047 after about five hours in coast. Fig. 2 compares the vertical beam-beam tune shift parameter ξ_y , calculated from the measured luminosity current ratio, with the beam-beam lifetimes of the e^+ and e^- beams. The beam-beam lifetime τ_{bb} is obtained as difference of the total measured lifetime τ and single beam lifetime τ_s according to:

$$\frac{1}{\tau_{bb}} = \frac{1}{\tau} - \frac{1}{\tau_s}$$

The 1994 data for single and separated beams is consistent with a constant value of $\tau_s = 45$ hours. In [4] it was shown that the expected beam-beam lifetime τ_{bb} follows ξ_y according to:

$$\tau_{bb} = \frac{2r_e m_e}{n_{cross} f \sigma} \frac{\beta_y^*}{E_b \xi_y} \approx 1 \text{ hour} / \xi_y$$

$\sigma \approx 0.21$ barn is the total e^+e^- cross-section leading to the loss of a beam particle. It is dominated by beam-beam Bremsstrahlung, or more precisely, since we are dealing with e^+e^- collisions, by radiative Bhabha scattering. The full kinematics of the process and the introduction of a cutoff parameter corresponding to the mean half-distance between the particles in the bunch is discussed in [5]. About the same result is obtained by introducing a cutoff corresponding to the beam height as advocated in [6].

The proportionality between ξ_y and beam-beam lifetime is well visible in fig. 2. Some additional losses are seen in the first hours of the fill and in particular during times of very high vertical beam-beam

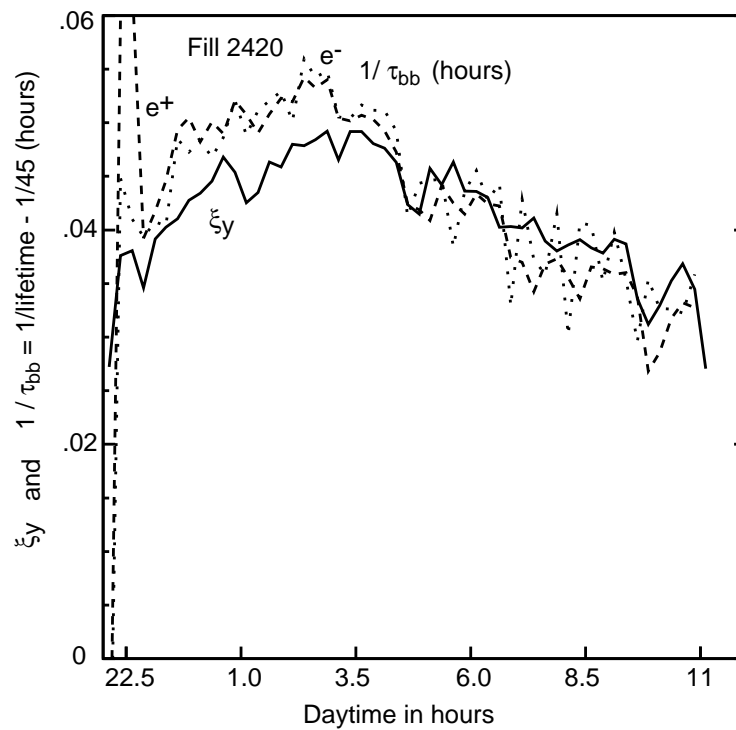


Figure 2: The vertical beam-beam tuneshift parameter ξ_y (solid line) and the inverse e^+ (dashed line) and e^- (dotted line) beam-beam lifetimes in 1/hours for the same fill.

tuneshifts. The additional losses reached about 1 % per hour (100 hours lifetime from extra losses). Still, the total lifetime stayed well above 10 hours. This can be seen in Fig. 3 which shows the same data again but this time directly as total measured and calculated lifetime in hours.

Attempts to collide higher currents or less favorable conditions like significant differences in currents of colliding bunches resulted in severe background or lifetime problems. A systematic study of the luminosity and beam current data of LEP coasts gave the following results

- Lifetimes for low currents are well explained by collision processes
- Observation of lifetimes below 10 hours imply significant extra losses
- Low lifetimes are often connected with background bursts seen by the experiments
- For similar running conditions, the probability for lifetime problems increases rapidly with current.

Operational experience has shown that the threshold for lifetime problems can be increased through

- a careful choice of the tune working point
- emittance control, - increasing the horizontal emittance using a wiggler
- increasing aperture, - using wider collimator settings

We believe that the lifetime and background problems are connected to losses by scraping into transverse beam-beam tails. It is difficult to localize losses and to optimize parameters for smooth running conditions based on studies of beam-current data. A much higher sensitivity can be achieved with loss monitors [7]. Scintillators have been installed in LEP at the aperture limiting collimators [8]. Recently, many more loss monitors using pin-diodes based on a design for HERA [9] were installed close to most collimators in LEP. Several measurements using loss monitors have been performed in recent machine development sessions and are being analyzed [10], [11]. First preliminary results will be discussed in the following chapter.

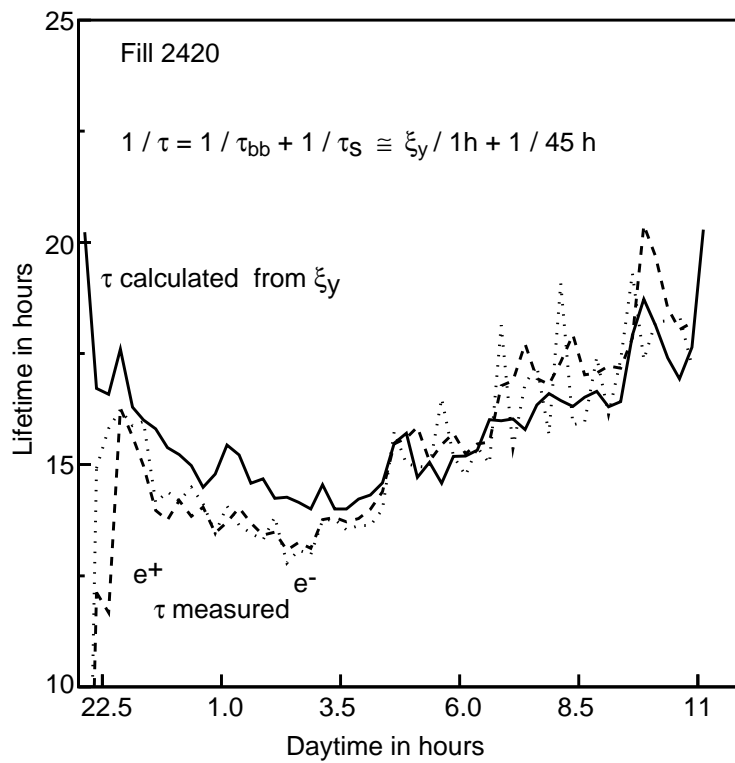


Figure 3: Total lifetime as obtained from fixed single beam lifetime and beam-beam lifetime via ξ_y (solid line) and measured e^+ (dashed line) and e^- (dotted line) lifetimes.

4 Beam-Beam Tails

Figures 4 and 5 show tail distributions as measured in two machine development sessions:

1) Fill 2364 on 4-9-94, 4x4 bunches, about $360\mu\text{A}$ per bunch, tails measured using pin-diode loss monitors

e^+ , e^- emittances were $\varepsilon_x = 40 \text{ nm}$ and $\varepsilon_y = 0.36 \text{ nm}$,

beam-beam tuneshift parameters $\xi_x = 0.025$ and $\xi_y = 0.042$.

Results are shown as solid lines for different settings of chromaticity (Q' between +5 and +10).

In the vertical plane tails were also measured with separated beams.

2) Fill 2724 on 10-6-95, 4x4 bunches, about $250\mu\text{A}$ per bunch, losses measured with scintillators

beams colliding, using '95 optics with vertical separation on either side of the interaction regions for bunch trains.

Rather unequal e^+ , e^- beam sizes, about 60 % higher e^- emittances in both planes.

e^- beam parameters were $\varepsilon_x = 44 \text{ nm}$ and $\varepsilon_y = 0.4 \text{ nm}$,

with beam-beam tuneshifts of $\xi_x = 0.025$ and $\xi_y = 0.035$.

Measurements were done for one machine setting with $Q'=10$ in both planes.

The results are shown as broken lines

Measurements were performed by moving one jaw of a collimator closer to the beam in steps. Beam current and beam size measurements were recorded for each collimator setting. The collimators were moved closer until significant lifetime reductions were observed. Lifetimes calculated from beam currents for these points were used to calibrate the loss monitors. This allows to give loss rates directly in terms of equivalent lifetimes from scraping. The uncertainty in the absolute calibration is

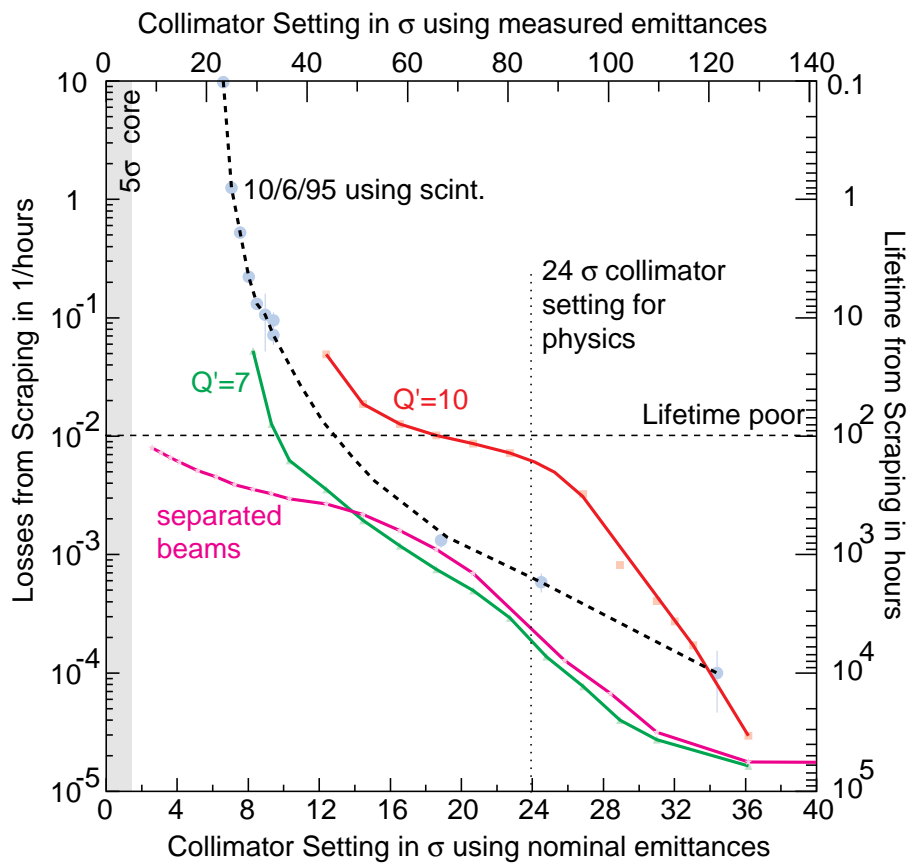


Figure 4: Measured beam tails in the vertical plane.

estimated to be about 30 %. There is some additional systematic error from noise and saturation for very high and low loss rates:

The pin-diode monitors are nearly noise-free but give only counts and saturate therefore at one hit per bunch passage. Measurements have been linearized using Poisson statistics.

The scintillators use pulse height information and did not reach saturation. Due to noise, these monitors are not sensitive to losses below 10^{-4} /hour.

The two different types of loss monitors are therefore rather complementary.

At the end of the second machine development scraping in the vertical plane was continued down to very low electron lifetimes in the order of minutes.

We distinguish between nominal and measured emittances. The nominal emittances are 45 nm for the horizontal and 4.5 nm for the vertical plane. Nominal emittances are very useful to compare collimator settings for various optics and positions around the ring. The values of 45 and 4.5 nm have been used in LEP for the last couple of years and still reflect quite well the maximum beam sizes observed in operation.

The collimator settings in figures 4, 5 are given in units of σ of nominal beam sizes. In addition, a second x-scale is shown on top of the figures using the measured beam sizes (measured beam sizes of both experiments were equal within errors of about 10 %). The expected gaussian core is illustrated as shaded area to 5σ using the measured emittances.

At this stage of measurements and analysis we found indications for:

- Non-gaussian transverse tails in both planes. Far tails and losses corresponding to lifetimes of order 10^3 hours were also recorded without colliding beams and might originate in processes like scattering on beam-gas or photons from black-body radiation

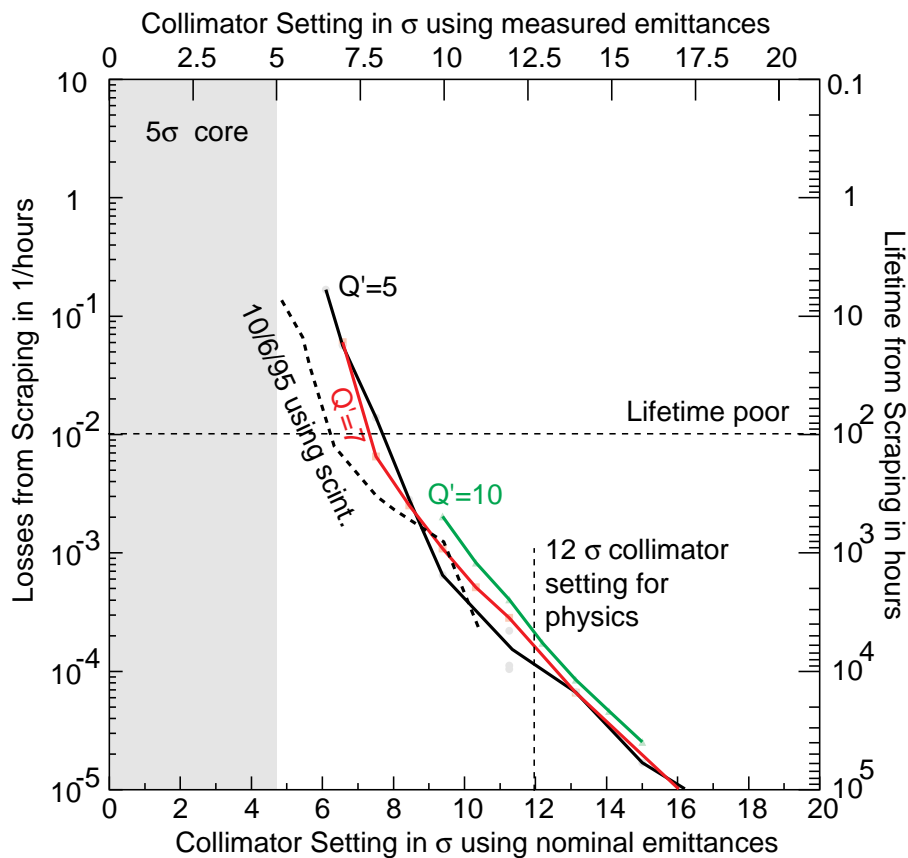


Figure 5: Measured beam tails in the horizontal plane.

- Very substantial non-gaussian beams are present for colliding beams in the vertical plane. High chromaticities increase vertical tails.

5 Summary

Lifetimes for single beams, separated beams and low-current colliding beams in LEP are well explained by known physics collision processes

- Compton scattering on black-body radiation photons
- Beam-Gas scattering
- Beam-Beam Bremsstrahlung

These collision processes result mainly in off-energy particles. If the energy loss exceeds the stable bucket height (about 1 % for LEP1) these particles will be lost, typically by hitting an aperture limit in a dispersion region.

Extra losses are seen for colliding beams and higher currents and have limited the maximum useful bunch currents at LEP1. They are attributed due to transverse tails generated by the beam-beam effect. Emittance blow up is observed for colliding beams in LEP in both planes. A wiggler is used to artificially increase the horizontal beam sizes and to avoid flip-flop and excessive tails. Very substantial tails are present for colliding beams in the vertical plane. More measurements and a detailed analysis including comparison with beam-beam simulation [12] are planned for the near future.

References

- [1] R.Bailey et al.; *Operational procedures to obtain high beam-beam tune shifts in LEP operation*, CERN-SL-95-49 OP and proceedings of PAC conference, Dallas 1-5 may 1995.
- [2] H.Burkhardt; *What is the maximum current we can collide at 45 GeV ?*, Proc. of the 5th LEP Perf. Workshop, Ed. J.Poole, CERN SL/95-08, pages 131-134
- [3] R.Bailey et al.; *LEP Operation in 1993 with the Pretzel Scheme*, Proc. 4th Europ.Part.Acc.Conf. EPAC London 1994, Eds. V.Suller and Ch.Petit-Jean-Genaz, Vol I page 439-441
- [4] H.Burkhardt, R.Kleiss; *Beam Lifetimes in LEP*, Proc. 4th Europ.Part.Acc.Conf. EPAC London 1994, Eds. V.Suller and Ch.Petit-Jean-Genaz, Vol II page 1353-1355
- [5] R.Kleiss, H.Burkhardt; *BBBREM: Monte Carlo Simulation of Radiative Bhabha Scattering in the very forward direction*. Comp.Phys.Commun.81:372-380,1994.
- [6] G.L.Kotkin, V.G.Serbo, A.Schiller; *Processes with Large Impact Parameters at Colliding Beams*. Int.J.Mod.Phys. A7 (1992) 4707-4745
- [7] S.Zholents; Presentation 78, 2nd workshop on LEP Performance, Ed. J.Poole, CERN SL/92-29
- [8] K. Cornelis et al.; *Commissioning of a Scintillator at the Aperture Collimators for the Study of Beam Tails*, SL-MD Note 60, October 1992.
- [9] W.Bialowons, F.Ridoutt, K.Wittenburg; *Electron Beam Loss Monitors for HERA*, Proc. 4th Europ.Part.Acc.Conf. EPAC London 1994, Eds. V.Suller and Ch.Petit-Jean-Genaz, Vol II page 1628-1630
- [10] H.Burkhardt, K.Cornelis, J.J.Gras, I.Reichel; *Scrapers and Tails*, SL-MD Note 175, June 1995
- [11] I.Reichel; University of Aachen/Germany and CERN, *work for Ph.D. thesis on transverse beam profiles in LEP*
- [12] T.Chen, J.Irwin, R.Siemann; *Simulation of the Beam-Beam Lifetime for LEP*, Proc. 4th Europ.Part.Acc.Conf EPAC London 1994, Eds. V.Suller and Ch.Petit-Jean-Genaz, Vol II page 1356-1358