Luminosity performance at high Energy

H. Burkhardt

Abstract

The performance achieved in terms of luminosity and beam-beam tune shift is reviewed and compared for the 90/60 and 108/90 optics, different energies and number of bunches used. The analysis includes a comparison with expected emittance ratios and a discussion of beam-lifetimes including quantum lifetime.

1 BEAM LIFETIMES

Beam lifetimes at LEP1 were well understood and could, except for occasional scraping into non-gaussian tails at the beginning of high current and high beam-beam tune shift fills, completely be accounted for by scattering processes [1]. Fig. 1 shows the observed e$^+$ and e$^-$ beam lifetimes for a LEP2 fill. The observed single beam lifetime of about 35 to 40 hours is about what was expected for LEP2 from Compton scattering on thermal photons and beam-gas scattering [2].

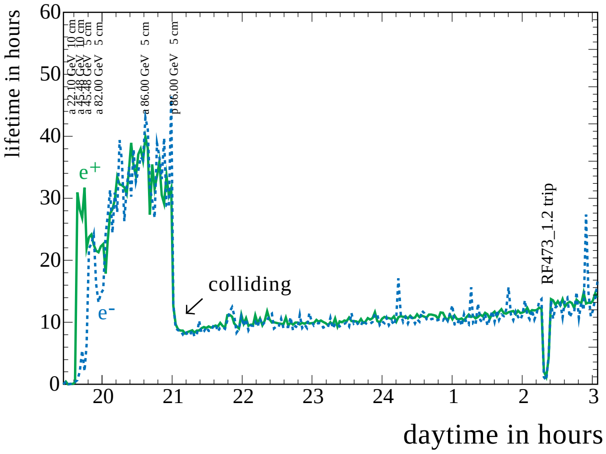

Figure 1: Total lifetime, example of fill 3716 (fill with highest luminosity, 90/60 optic, 2-11-96)

The expected lifetime from collisions in n interaction regions is:

$$\tau_b \;=\; \frac{2 r_e m_e}{n\ f_{rev.}\ \sigma_b} \cdot \frac{\beta_y^*}{E_b\ \xi_y}$$

The predicted cross section σ_b for LEP2 is about 0.23 barn, compared to typically 0.21 barn at LEP1. The "screened" cross section is independent of energy and the small increase in cross section from LEP1 to LEP2 due to the decrease in energy acceptance or bucket half height from typically 1.3 % at LEP1 to 1.0 % at LEP2. Measured and expected lifetimes in collision agree very well as shown in Fig. 2. Safe RF-operation requires some overvoltage such that losses from quantum lifetime are negligible with all RF-units turned fully on. The dip in lifetime in fill 3716 at about 2:30 in the morning visible in Fig. 1 occurred in coincidence with a trip of RF stations 473_1 and 473_2 and is attributed to losses in quantum lifetime.

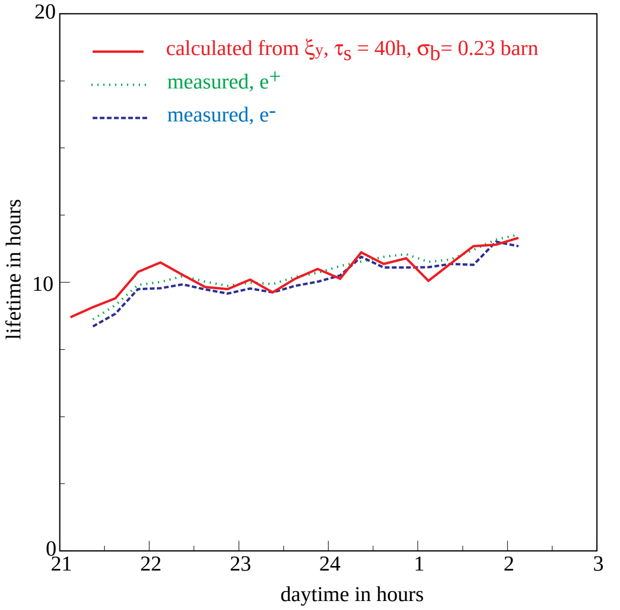

Figure 2: Lifetime in collisions in fill 3716 as measured and expected from luminosity and vertical beam-beam tune shift ξ_y.

The quantum lifetime τ_q is a steep function of

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

According to Sands[3], the quantum lifetime is given by:

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

Francesco Ruggiero suggested a different treatment close to the bucket boundary and obtained[4]:

$$\tau_q = \frac{1}{f_{rev.} Q_s} \exp\left(\frac{n_\sigma^2}{2}\right)$$

Numerical values (at 90 GeV and for a longitudinal damping time of $\tau_e = 4.2$ ms are):

$n_\sigma =$ s_b/σ_e	n_σ^2 / 2	Sands τ_q, [h]	Ruggiero τ_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

Even though quantum lifetime is the main limitation on the maximum beam energy at LEP2, no dedicated measurements and studies have been done on this subject in 1996. Expected and observed quantum lifetimes are shown in Fig. 3. The two top plots contain measurements of the e$^+$ and e$^-$ quantum lifetimes determined as part of an MD on the 25-11-95. The lifetimes observed were longer than expected. Standard operation in 1996 at 86 GeV in the 90/60 lattice was using a total voltage of V_{RF}=1920 MV corresponding to Q_s=0.0106. A trip of one RF-unit of 80 MV reduced this to 1840 MV total or Q_s=0.098 without any problems in quantum lifetime. A second trip typically resulted in 1760 MV or Q_s=0.088 with severe quantum lifetime problems as expected from Fig. 3. The two right hand side plots in Fig. 3 include quantum lifetimes observed in fills in operation (fill 3126 at 65 GeV in 1995 and the attempt to ramp to the highest possible energy in fill 3621 in 1996).

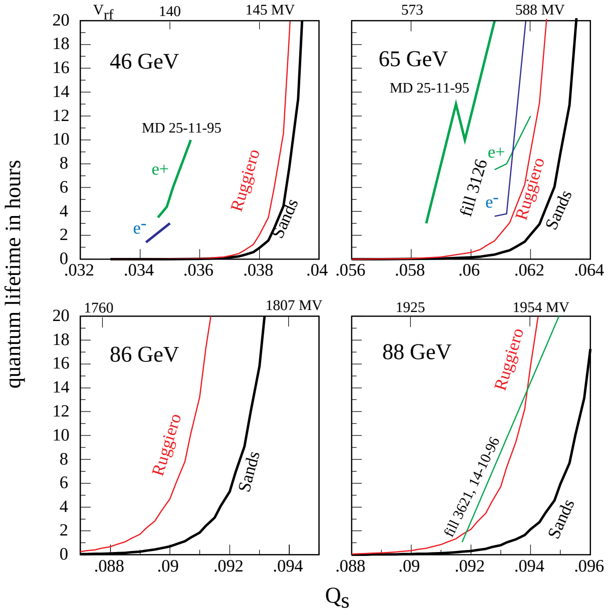

Figure 3: Expected and observed quantum lifetimes at four different energies as a function of the synchrotron tune Q_s. For comparison, some values of Q_s have been converted into RF-voltage and are shown at the top of the figures.

Even though systematic errors in the measurements have not been estimated and may be significant, it is also possible that the differences are real and can be explained by a more detailed model. Small, often neglected effects in the prediction of quantum lifetime are:

- imperfect dipole magnet model (using rectangular magnets with constant ρ)
- synchrotron radiation from quadrupoles
- energy losses other than synchrotron radiation like parasitic RF-losses
- uncertainty in the real beam energy and central orbit frequency
- uncertainty in the momentum compaction α_c including higher orders
- discreteness in stepping through the separatrix for large Q_s
- difference between coherent and incoherent Q_s
- the synchrotron spectrum is not extending to infinity
- neglection of the variation of the energy loss U_0 per turn at the bucket boundary compared to the nominal energy in the calculation of the bucket height

The last point in the list above, concerning the calculation of the bucket height is further illustrated in Fig. 4. The energy loss per turn at a beam energy of 90 GeV in LEP2 is 1.918 GeV or more than 2 % of the beam energy. The simple tracking shown in Fig. 4 suggests, that a particle with an energy offset of -1.02 % can still be captured while the standard (Sands) bucket height is only 0.94 %. The tentative explanation is that a particle at the lower bucket limit has less energy and less synchrotron radiation. In the example chosen here the loss per turn would be 1.882 GeV compared to U_0 of 1.918 GeV. Assuming an RF-voltage of 2.151 GV, this corresponds to an overvoltage of 269 MV at the bucket boundary compared to 233 MV for the bucket centre or a difference of 36 MV equivalent to nearly one LEP2 RF-station. The same effect is expected for a particle launched slightly outside the top of the bucket. It would initially loose more energy but could still spiral into the lower half of the standard bucket.

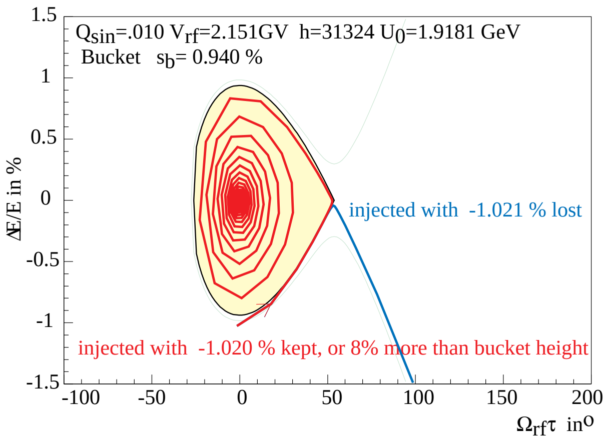

Figure 4: Result of simple tracking in the longitudinal coordinate.

2 LUMINOSITY, TUNE SHIFT AND EMITTANCE RATIO

The performance achieved is shown in terms of the vertical beam-beam tune shift parameter ξ_y as function of the current per bunch. Each point in tune shift is calculated from the average luminosity recorded by the four LEP experiments over time intervals of 15 minutes. Dots are used for running with 8 bunches and crosses for running with 4 bunches. Fig. 5 shows the performance in the three fills at Z-energy just after the restart of the machine in october. We see the typical behaviour of running at LEP1 energy at the beam-beam limit. The fills are with bunch trains and $4 \cdot 2 + 4 \cdot 2$ bunches. It is interesting to note that tune shifts up to about 0.04 were reached in fill 3631, or rather quickly after the restart of the machine. For comparison, the average tune shifts in $4 \cdot 3 + 4 \cdot 3$ running at Z-energies with bunch trains in 1995 were 0.023 with best values up to 0.03 [5].

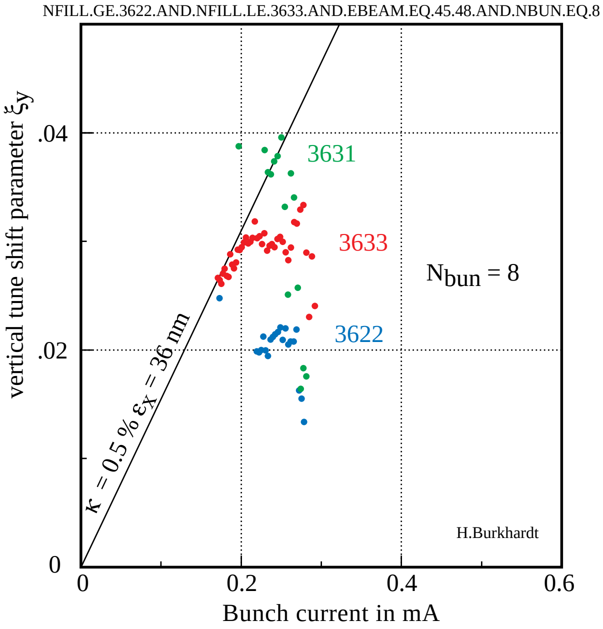

Figure 5: 90/60 optics, 45 GeV

Operation at LEP2 energies has so far not been beam-beam limited. Tune shifts were proportional to bunch currents as can be seen from Figs. 6, 7, 8. The figures include the expected dependence of ξ_y on current, based on the natural horizontal emittance and a fixed emittance ratio $\kappa = \varepsilon_y/\varepsilon_x$. Lines of constant luminosity are also shown for the case of 4+4 bunches. For 8+8 bunches and the same ξ_y and bunch current, the luminosity would be two times higher. Fig. 6 summarizes the LEP2 operation up to the stop in september 1996. The average emittance ratio was 1 % and very similar beam-beam tune shifts were observed in 4+4 and 8+8 operation. Conditions improved quickly, when the machine was restarted in october. As can be seen in Fig. 7, average emittance ratios were about 0.4 % and peak tune shifts exceeded 0.04. It is not quite clear, why the performance improved after the summer stop. Since identical optimization methods were used, it is likely that the improvement is coming from changes in the hardware like the realignment of some quadrupoles in the insertions.

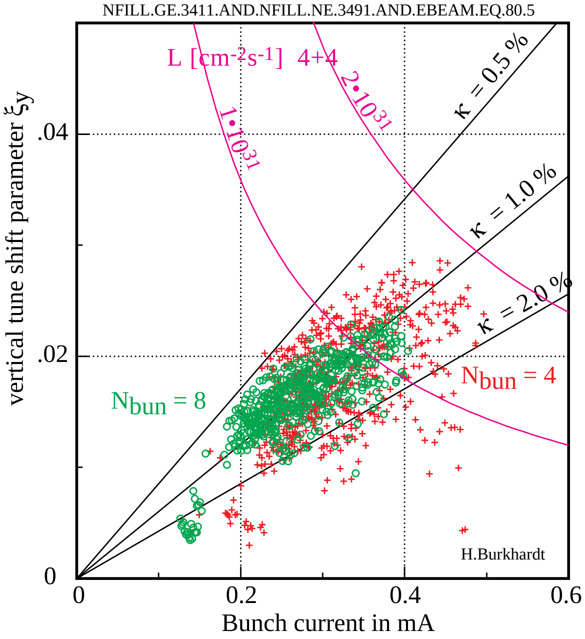

Figure 6: 90/60 optics, ε_x=37 nm, 80 GeV

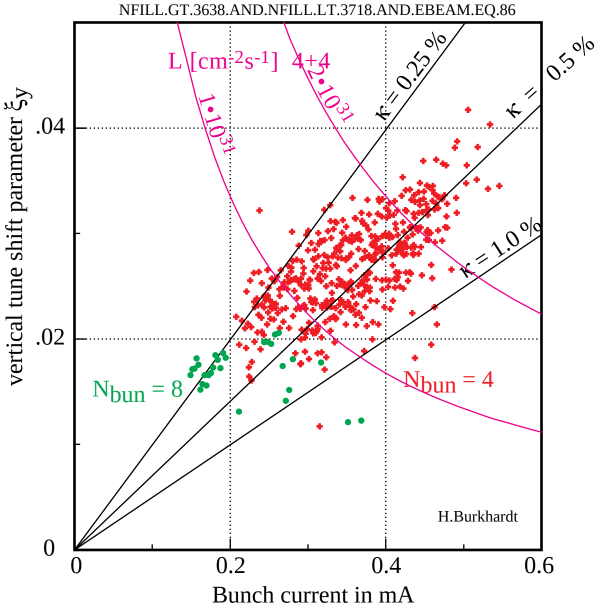

Figure 7: 90/60 optics, ε_x=42 nm, 86 GeV

The performance in terms of beam-beam tune shift of the last running period of 1996, using the 108/90 optics is shown in fig. 8. The average coupling ratio was only about 1.5 % such that the overall performance was not as good as with the 90/60 optics in spite of the decrease in horizontal emittance.

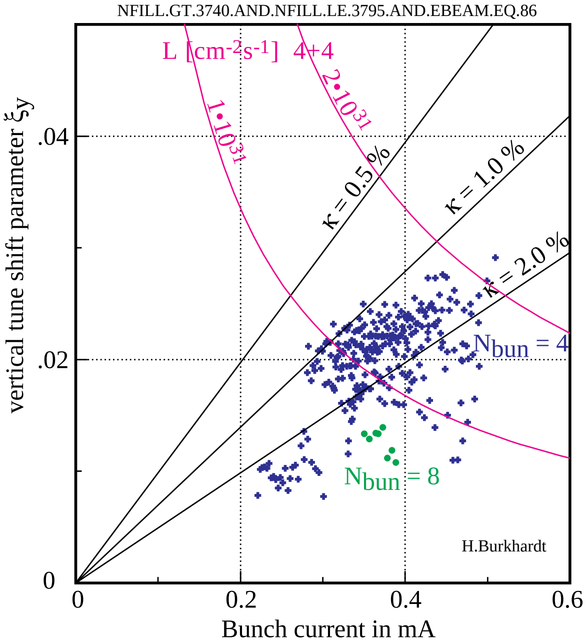

Figure 8: 108/90 optics, ε_x=30 nm, 86 GeV

3 SUMMARY

Lifetimes were typically:

- 35 to 40 hours for single beams (10 h means bad vacuum)
- about 0.5 hours / ξ_y from collisions

or in both cases as expected. The RF-limit and quantum lifetime are not so well understood yet and deserve further studies.

Tune shift and emittance ratios:

- with $4 \cdot 2 + 4 \cdot 2$ bunches at 45 GeV in bunch trains, tune shifts reached quickly values up to about 0.04 in fill 3631
- up to the highest bunch currents (about 500μA so far), LEP2 operation has not been beam-beam limited
- similar ξ_y and κ were observed for the same bunch current in 4+4 and 8+8 operation.

90/60 optics:

- the running before the summer stop gave tune shifts up to 0.03, a mean $\kappa \approx 1\ \%$ and best $\kappa \approx 0.6\ \%$.
- performance significantly improved (machine changed ?) after the stop in october with ξ_y reaching 0.04, a mean $\kappa \approx 0.4\ \%$ and best $\kappa \approx 0.25\ \%$.

108/90 optics:

- a mean $\kappa \approx 1.5\ \%$ and best $\kappa \approx 1\ \%$ and tune shifts up to 0.03 were observed

4 APPENDIX

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

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

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

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

$$s_b = \sqrt{\frac{2U_0}{\pi \alpha_c h E_b} (\frac{\pi}{2} - \phi_s - \text{ctg } \phi_s)}$$

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

5 REFERENCES

[1] 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

[2] H.Burkhardt; Beam-Beam Tuneshift, Emittance and Lifetime, Presentation 55, Proceedings of the 4th workshop on LEP Performance, Ed. J.Poole, CERN SL/94-06 (DI)

[3] M.Sands, SLAC-121, (1970)

[4] F.Ruggiero, A correct formula for the longitudinal quantum lifetime in electron storage rings, CERN SL/93-05 (AP)

[5] H.Burkhardt; Performance in Physics, Proceedings of the 6th workshop on LEP Performance, Ed. J.Poole, page 160-163, CERN SL/96-05 (DI)