Presentation 35

Lifetime and Beam-Beam Limit

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35.1 Introduction

Long beam lifetimes, more than 40 hours for single or separated beams and about 20 hours for colliding beams, are typical in stable running conditions. The dominant loss mechanisms are scattering on thermal photons [1] for single beams and beam-beam Bremsstrahlung for colliding beams [2]. Occasionally, partial beam losses and much shorter lifetimes are observed. This will be analysed in this presentation.

35.2 Collimators, Aperture

The theoretical energy aperture or bucket (-half) height s_b is [3]:

$$s_b = \sqrt{\frac{2U_0}{\pi\alpha_c h E_b}(\frac{\pi}{2} - \phi_s - \text{ctg } \phi_s)} \approx 0.013 \quad \text{for LEP 1993 conditions}$$

U_0 is the energy loss in synchrotron light per turn, α_c the momentum compaction factor and ϕ_s the stable phase angle. The numerical value has been calculated using a beam energy E_b=45.6 GeV, $\alpha_c = 1.86 \cdot 10^{-4}$ and $Q_s = 0.065$. Using the program of [1], this corresponds to a lifetime from Compton scattering on thermal photons of $\tau_{th} = 88$ hours. The longest single beam lifetime observed in 1993 was $\tau_s = 61 \pm 4$ hours (Fill 1896, collimators in ramp&squeeze, unsqueezed, separated Pretzel 8x8 beams, 1.4 mA total e^+ and 0.5 mA total e^- currents). A 61 hour lifetime corresponds to an energy aperture of 0.8 % or, assuming the theoretical aperture, to other loss mechanisms like beamgas with $\tau_{rest} \approx 200$ hours. With squeezed beams and collimators in physics settings, the longest observed lifetimes are $\tau_s = 49 \pm 2$ hours (Fill 1897, Pretzel 8x8 bunches, separated, total 0.7 mA e^+ and 0.5 mA e^- currents).

This suggests, that the energy aperture is reduced in physics conditions (squeezed optics and collimators in physics settings). It is confirmed by tracking of off-momentum electrons with Decay-Turtle[4]: particles with energy deviation of 0.7 % were found to start to hit collimators, in particular COLH.QF33.L3. This collimator is placed in a region with horizontal dispersion ($D_x = 1.11$ m). The setting is at 10 σ, where

$$\sigma = \sqrt{\beta\epsilon + (D\frac{\Delta E}{E})^2}$$

assuming an emittance of $\epsilon = 45$ nm and an energy spread of $\frac{\Delta E}{E} = 10^{-3}$. The various collimator families and typical background conditions have been discussed in previous LEP-Performance workshops [5], [6]. Already in previous years, background conditions were generally very satisfactory. As proposed in [7] and [8], a so called H-optics with $\beta_x^* = 2.5$ m was used in physics conditions during most of 1993, resulting in a further decrease of background to the experiments.

The effect of aperture collimators in physics conditions was studied in a machine development session

[9]. A factor of five reduction of background rates was observed in the ALEPH TPC, when the first set of aperture collimators, the vertical aperture collimators, were moved to their physics position (at 20 σ assuming $\epsilon_y = \epsilon_x$ / 10). The effect of the horizontal and energy aperture collimators, that were moved in later, was less significant for the background rates observed in the experiments. There was not enough time available in the machine development session, to make precise lifetime measurements in the various conditions. It seemed however, that operation with aperture collimators in physics conditions was more critical and particularly sensitive on the (tune-) working point.

For 1994 we propose to use wider settings for aperture collimators. The aim is to maximize aperture with tolerable background conditions. To give a quantitative example: For the horizontal collimators at the experiments (COLH.QS1, 8.5 m from the IP's), a setting of 32 mm or 15 σ gave good background conditions. A setting at 35 mm or 17 σ should still be very acceptable for the experiments. The 120 m horizontal collimator (COLH.QS6) would have to be opened as well from the present 11mm or 13 σ to 14.2 mm or 17 σ. If backgrounds to the experiments would be acceptable, a protection with aperture collimators could now be obtained with 15 rather then the usual 10 σ, corresponding to a gain in emittance of over two.

35.3 The effect of the emittance Wiggler

Fig. 35.1 illustrates the use of the emittance wiggler. The beam-beam tuneshift parameter ξ increases linearly with current i until it reaches saturation. A constant ξ at higher bunch currents i_b implies, that the emittance has to grow proportional to current. With still increasing currents, there is tendency for the so called flip-flop effect: Either the e^+ or the e^- blows up strongly, while the other beam reduces in beam size close to its natural emittance. This can be avoided by using a controlled blow up in the emittance of both beams using the emittance wiggler.

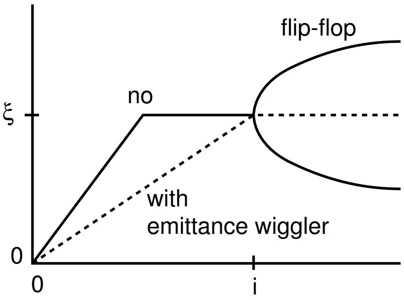

Figure 35.1: Illustration of increase of the beam-beam tuneshift parameters ξ with the bunch current i with and without the use of the emittance wiggler.

Table 35.1 gives the expected emittance as function of the emittance wiggler excitation. The effect on

Emittance Wiggler Tm	U_0 MeV	σ_E 10^{-3}	ϵ_x nm	$\xi = 0.03$ i, μA
0.04	126.4	0.72	11.9	128
0.24	127.5	0.73	12.5	134
0.44	130.2	0.80	15.5	167
0.54	132.2	0.87	18.6	200
0.64	134.5	0.96	23.0	248
0.74	137.3	1.06	28.9	311
0.84	140.4	1.19	36.3	391

Table 35.1: Energy loss per turn U_0, relative energy spread σ_E, horizontal emittance ϵ_x and bunch current at which $\xi = 0.03$ is reached, as function of the emittance wiggler excitation for the g05p46h optics used in 1993 physics operation.

the total energy loss per turn and the relative energy spread is also given. The entries in table 35.1 have been obtained from a simple calculation using dipole pieces. The result was checked to be consistent with the MAD and WIGWAM programs [10].

The standard formulas for the horizontal and vertical beam-beam tuneshift parameters are:

$$\xi_x = \frac{r_e m_e}{2\pi e f E} \cdot \frac{i\,\beta_x^*}{\sigma_x^2} = \frac{r_e m_e}{2\pi e f E} \cdot \frac{i}{\epsilon_x} \qquad \xi_y = \frac{r_e m_e}{2\pi e f E} \cdot \frac{i\,\beta_y^*}{\sigma_x \sigma_y} \tag{35.1}$$

The rightmost column in table 35.1 gives the bunch current i, that is needed to reach a value of $\xi_x = 0.03$.

In typical operation, beams were collided using the maximum excitation of the emittance wiggler of 0.84 Tm. However, to get reasonable luminosities and tuneshifts close to 0.03, the emittance wiggler had generally to be lowered to about 0.64 Tm. This was not expected. It is probably connected to unwanted side effects of wigglers, like the increased energy spread and therefore more significant contribution of dispersion to the beam size.

35.4 H and L optics

In previous years, LEP was always operated with a ratio $\beta_y^*/\beta_x^* = 4\%$. For 1993, both an L-optics with the usual 4 % beta ratio and an H-optics with a beta ratio of 2 % were available. Table 35.2

Optics	β_y^*	β_x^*	β_y^* / β_x^*	β_x at COLH.QS1
H	5 cm	2.5 m	2 %	100 m
L	5 cm	1.25 m	4 %	180 m

Table 35.2: Beta values in the H and L optics at the interaction points and at the 8.5 m collimators.

gives the beta values used in physics in both cases. The advantages of the H optics are:

- Smaller β_x in close quadrupoles and collimators, allowing lower backgrounds (used) and more aperture (not yet used).
- Larger beam sizes by factor $\sqrt{2}$ at the interaction point, making residual horizontal separation (Pretzel) less problematic.

Potential drawback:

- A smaller vertical beam size is needed for the same luminosity. Coupling, dispersion and residual vertical separation will be more critical to control.

At low currents, beam sizes are determined by the natural horizontal emittance ϵ_x and the coupling $\kappa = \epsilon_y/\epsilon_x$. The beam-beam tuneshift parameters increase linearly with current until they reach some asymptotic value, typically $\xi_{asym} = 0.03$. According to equation 35.1, the beam-beam limit in the horizontal plane is reached at the current:

$$i = \frac{2\pi e f E}{r_e m_e} \cdot \epsilon_x \cdot \xi_{asym}$$

The vertical tuneshift depends on both the horizontal and vertical beam size and therefore the coupling. From equation 35.1 we get:

$$\xi_y = \xi_x \cdot \sqrt{\frac{\beta_y^*}{\kappa \beta_x^*}}$$

Both tuneshift parameters are equal if the coupling is matched to the β ratio according to $\kappa = \beta_y^*/\beta_x^*$. For a smaller coupling, the vertical tuneshift shift can be kept at its asymptotic value down to lower currents (and therefore the luminosity increased at these currents). If the coupling exceeds the β ratio, then the vertical beam size will be always determined by coupling and never reach its asymptotic value leading to a loss in luminosity at all currents. Both cases are illustrated in figure 35.2.

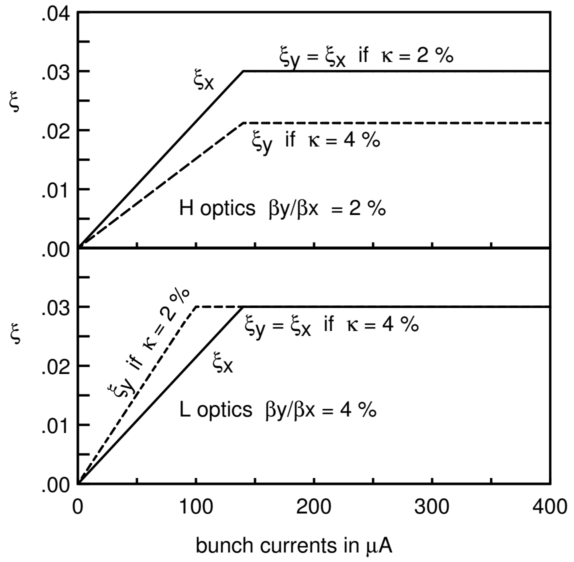

Figure 35.2: Dependence of tuneshift parameters $\xi_{x,y}$ on current.

35.5 Observed beam-beam tuneshift parameters

The observed vertical tuneshift parameters for the 1993 Pretzel running are shown in fig. 35.3. They have been calculated from the measured luminosities according to:

$$L = \frac{E\, i\, k\, \xi_y}{2 e r_e m_e\, \beta_y^*}$$

The horizontal tuneshift parameters have been calculated using the emittance as calculated from the beam sizes measured by the BEUV (using the calibration of R.Jung et al. from June 1993). It is instructive, to compare figures 35.3, 35.4 with the corresponding figures from 4x4 and 8x8 running in 1992 [11]. A clear improvement is visible for the vertical beam-beam tuneshift, compared to Pretzel operation in 1992.

As already observed in 1992 and in contrast to 4x4 operation, the horizontal tuneshifts in Pretzel operation tend to decrease with current. The horizontal tuneshift parameter for the positrons ξ_x^+ was in average significantly higher in 1993 than the horizontal tuneshift parameter for the electrons ξ_x^- (smaller e^- beam, more blow up on e^+). With large horizontal Pretzel amplitudes, residual tuneshifts from the close encounters in the arcs and small horizontal miss-crossings at the interaction points, it is not too surprising that the control of the horizontal emittances and tuneshifts is more difficult in Pretzel operation than in 4x4 operation.

35.6 Analysis of lifetime problems

Beam currents were extracted from the database and lifetimes calculated for all physics fills in 30 minute intervals. All cases of lifetimes of $\tau < 10$ hours, which is significantly below the typical 20 hours and corresponds to > 2.5 % extra current loss, have been looked at. 69 Pretzel fills among the 147 that have been studied had significant lifetime problems. As shown in fig. 35.5, physics fills started with in average more positron current (+2% current asymmetry) than electron current. This was done intentionally, since it was well known in operation, that the positrons tended to be the weaker beam. In fact we see from fig. 35.5 that fills ended in average with lower positron currents (-4% asymmetry).

Table 35.3 gives the mean currents and emittances for all cases and for intervals with lifetime problems ($\tau < 10$ hours). The average emittance of the positron beam (34.4 nm) is significantly higher than

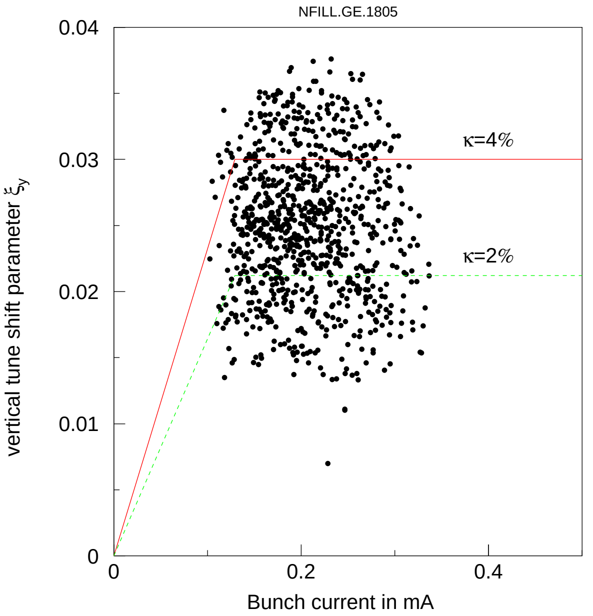

Figure 35.3: ξ_y dependence on current in Pretzel operation 1993. The expected behaviour for a coupling of $\kappa = 2$ and 4 % is also shown.

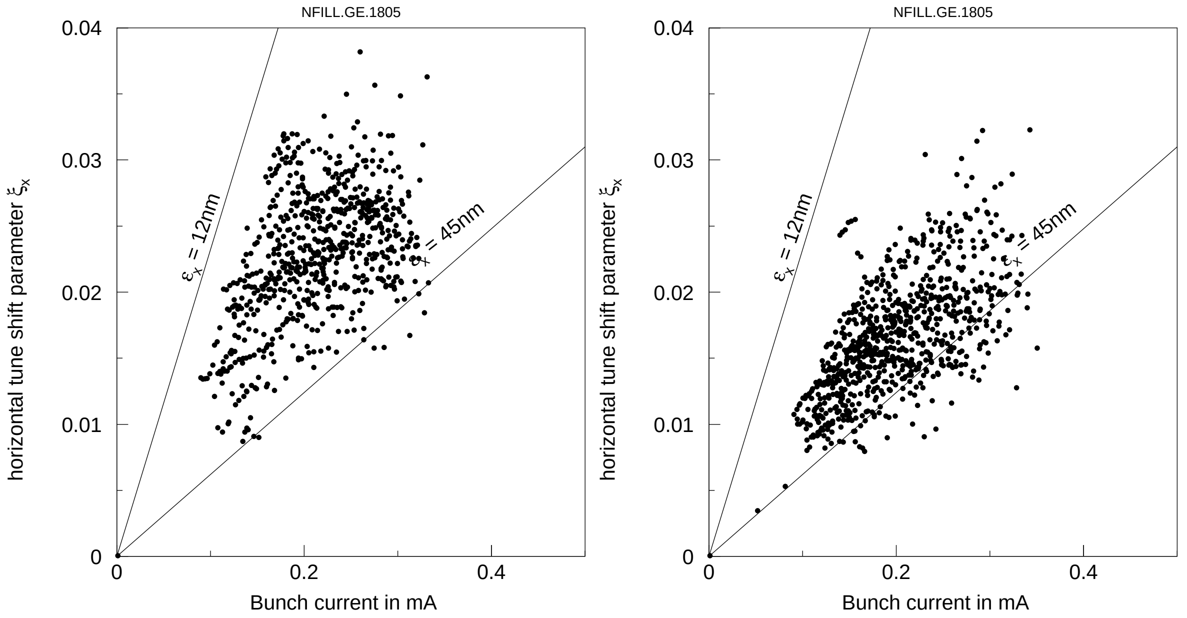

Figure 35.4: ξ_x dependence on current in Pretzel operation 1993. The expected behaviour for a constant emittance of 12 and 45 nm is also shown. The left plot shows $\xi_x^+ \propto i^- / \epsilon_x^-$ and the plot on the right $\xi_x^- \propto i^+ / \epsilon_x^+$.

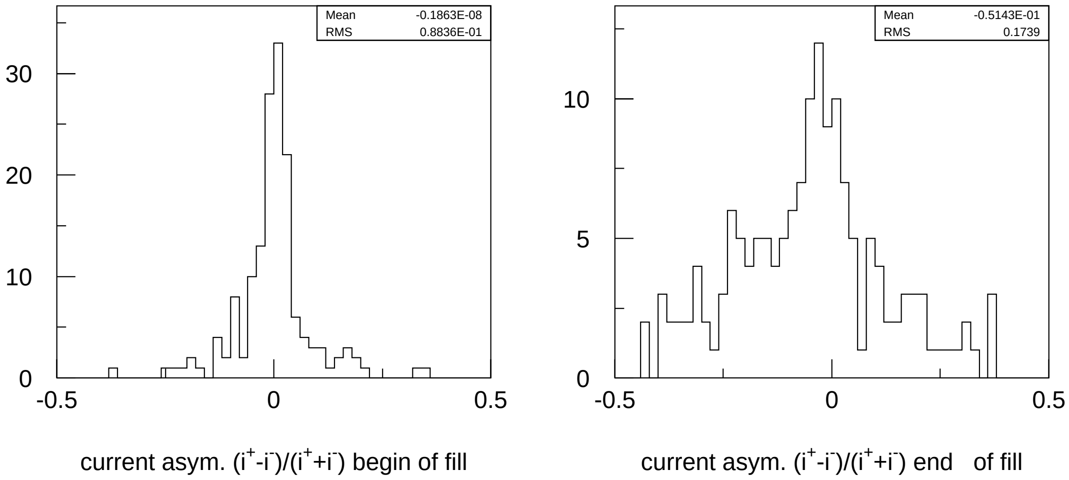

Figure 35.5: Positron-electron current asymmetry $(i^+ - i^-)/(i^+ + i^-)$ at the beginning and end of 1993 Pretzel physics fills.

category	entries	i^+ mA	i^- mA	ϵ_x^+ nm	ϵ_x^- nm
all	1857	0.202	0.217	34.4	26.8
$\tau^+ < 10$ h	137	0.209	0.267	42.9	32.0
$\tau^- < 10$ h	28	0.264	0.284	42.5	33.9

Table 35.3: Mean e^+ and e^- beam currents and emittances for 1993 Pretzel fills, from any 30 minute interval and from intervals with lifetime problems.

for the electron beam (26.8 nm). Lifetime problems are clearly correlated with high emittances (in average 42.9 nm for the positrons) and with high currents in the opposite beam. Operationally it was observed, that the lifetimes were very sensitive to tune (in particular Q_x) and chromaticity (high Q' should be avoided).

35.7 Conclusion, Improvements

Overall, the 1993 Pretzel running with the H-optics was very successful. High ξ_y tuneshifts close to the best 4x4 performance were reached. Due to the smaller β_y/β_x ratio, very careful vertical steering (golden orbit, frequent vertical vernier scans) was necessary for good performance.
Lifetime problems were clearly correlated with:

- high currents
- high emittance
- beam-beam, e^+/e^- flip-flop

In 1993 Pretzel running, there was a clear tendency for an e^+/e^- asymmetry. In spite of higher positron currents at the beginning of fills, the positrons tended to be the weaker beam with more blow up and lifetime problems. About half of the Pretzel fills 1993 had significant lifetime problems and bunch currents above 300 μA were increasingly difficult to handle. The performance of Pretzel operation could be further improved by:

- maximising aperture with acceptable background
- more loss monitors, higher BCT precision, good Q, Q' measurements in physics for faster and more specific diagnosis of lifetime problems
- understand and cure: e^+ blow up in Pretzel and poor performance at high excitation of the emittance wiggler.

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