The Effect of the Beam–Beam Interaction on the Performance of LEP

H.Burkhardt, A.Hofmann, Y.Marti, S.Myers, J.Poole
CERN-SL
CH-1211 Geneva 23

Abstract

During 1990 the LEP collider was operated at tune values just above the integers 71 and 77 (horizontally and vertically respectively). Measurement of the specific luminosity during this period showed it to increase substantially during the course of each fill; i.e. as the intensity dropped. Beam-beam simulations predicted the same behaviour, and showed that higher specific luminosity should be obtained by operating at integer tunes just above 70 and 76 [1]. During 1991 the new optics 70/76 was used for physics and found to give much higher specific luminosities. In addition, the intensity at injection energy seemed to be limited by residual horizontal beam–beam effects even with the beams separated. The β_x^* at injection energy was then reduced by a factor of two in order to reduce the residual beam-beam strength (ξ_s). This allowed higher currents to be accumulated.

1 INTRODUCTION

The performance of LEP is limited by the beam-beam forces in two main areas of operation. Firstly, at injection energy, the current per beam which can be accumulated with two counter-rotating beams (which are vertically separated at the encounter points) is less than the single beam limit. This limit is due to the *residual* beam-beam forces which the bunches exert on each other at each encounter point even though they are vertically separated. The second and even more serious limitation is at collision energy where the strong non-linear electromagnetic forces associated with the charged bunches cause an increase in their transverse size and hence a reduction in the luminosity. More recently, at higher currents, transverse coherent oscillations have been observed when the bunches are brought into collision. These oscillations have occurred in both the horizontal and the vertical planes and could be eliminated by a large increase in the chromaticity.

The design parameters for LEP are four bunches per beam of 750 μA per bunch. At Z^0 energies the horizontal emittance for the 60° phase advance per cell optic is around 36 nm and the design emittance coupling is 4%. Under these conditions the "unperturbed" beam-beam strength parameter (ξ_0) is .06 in each of the four experimental points. In the other four experimental points the beams are separated using electrostatic separators. Beam-beam simulations have shown that the beam-beam limit ($\hat{\xi}$) under these conditions is about .04.

2 RESIDUAL BEAM–BEAM EFFECTS

For beams with large separations ($\delta >\sim 3\sigma$), the beam-beam strength parameters are conveniently given by:

$$\xi_{xs} = \frac{n_b\, r_e}{2\pi\gamma}\frac{\beta_x^*}{\delta^2} \qquad \xi_{ys} = -\frac{n_b\, r_e}{2\pi\gamma}\frac{\beta_y^*}{\delta^2} \tag{1}$$

where n_b is the number of particles per bunch, and $\gamma = \frac{E}{m_e c^2}$ the Lorentz factor.

For LEP at injection energy of 20 GeV, with a bunch current of 500μA, and the nominal values of β^*s

$$\xi_{xs} = .0057 \quad and \quad \xi_{ys} = .0002$$

From equation (1) the ξ_{xs} may be varied either by varying the β_x^* or by varying the electric field in the separators and thereby the amount of vertical separation (δ). The latter was first tried as a machine experiment and the maximum current which could be accumulated was recorded. Fig. 1 shows plots of the results as well as the calculated ξ_{xs}.

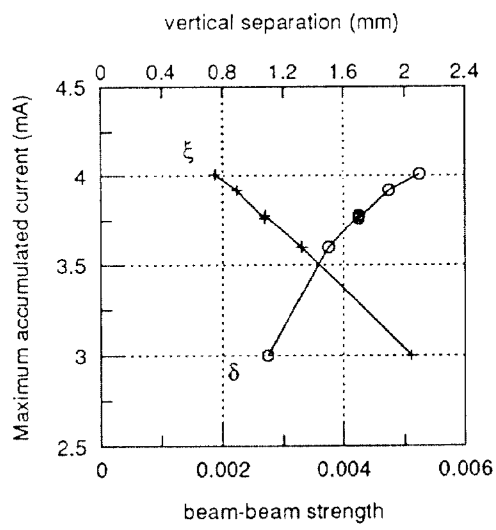

Figure 1: Influence of the vertical separation δ on the maximum accumulated current

Clearly, increasing the separations beyond the nominal maximum of 1.7 mm improves the maximum current which can be accumulated. The all-out maximum separation which could be attained in this experiment was 2.1 mm and this was made available by reducing the gap separation in the separators. It is also interesting to note that the residual ξ is nearly linear with the beam current and that a value of ξ extrapolated to zero corresponds to 4.7mA which is close to the maximum single beam current of around 4.8mA. Following these results the gaps of the separators were reduced for physics with only a small increase in the spark rate after some conditioning with beam.

In addition a new optics was generated which had a β_x^* reduced by a factor of 2 at injection energy, thereby reducing the ξ by the same amount. This new optics was also conceived to maintain constant the ξ as the energy is ramped. The combined result of both measures reduced the residual ξ by more than a factor of 4. These conditions were used for physics during the last period in 1991 and resulted in the accumulation of more than 4 mA in nearly every fill with a maximum of 4.6 mA.

3 OBSERVATION OF BEAM-BEAM EFFECTS IN COLLISION

During the 1991 LEP-running, one priority objective was to increase intensities at injection energy and minimize losses during the ramp and squeeze, in order to maximize the currents in collision and with it, the luminosity. From October 1991 on, by combining the ramp and squeeze procedure, currents in excess of 4 mA became available at 45 GeV at $\beta^* = 5$ cm. At these currents, drastic changes were observed when the beams were brought into collision. The vertical beam size, as observed with synchrotron light monitors, increased by ≈ 30 % on average, and the lifetime of some bunches, decreased significantly. In LEP fill 820 for example, from initially ≈ 500 μA per bunch and excellent lifetime, after 30 minutes in collisions, the following currents remained:

bunch	I e^+ [μA]	I e^- [μA]
1	**485**	**479**
2	126	248
3	**481**	**477**
4	119	253

Collisions in LEP take place between even and odd numbered positron (p1, p2,...) and electron (e1, e2, ...) bunches according to :

IP 2, 6 : p1e2 + **p2e3** + p3e4 + p4e1

IP 4, 8 : p1e4 + p2e1 + **p3e2** + p4e3

The strong bunches generally remain with good lifetime and the weak bunches are blown up with bad lifetime. Similar problems were found in subsequent fills with some dependence on tunes and little dependence on the orbit. Operationally it was observed, that beam losses coincided with transverse coherent bunch oscillations and that these could be reduced by increasing the chromaticity.

Reduction of the lifetime with the setting of the collimators, and the high levels of background suggested the presence of non-gaussian tails in the transverse beam dimensions.

Data on luminosity as observed by the experiments and the bunch currents in LEP are logged at regular intervals. This data is used to display the performance of LEP online in the control room. Together with the information on β^* and beam energy, this data is used to calculate the beam–beam parameter ξ_y.

Towards the end of a fill, the vertical beam size σ_y tends to remain constant, so that the luminosity L varies as $\propto 1/I^2$ and the specific luminosity approaches a constant value:

$$L_{sp} = \frac{L}{I^2} = \frac{1}{4\,\pi\,e^2\,k\,f_{rev}} \cdot \frac{1}{\sigma_x^*\sigma_y^*} \quad ,$$

where I is the total e^+ or e^- beam current of k bunches (k=4 in 1991).

$$\xi_{x,y} = \frac{r_e\;n_b\;\beta_{x,y}^*}{2\pi\gamma\,\sigma_{x,y}^*\,(\sigma_x^* + \sigma_y^*)}$$

With $\sigma_x \gg \sigma_y$, the horizontal tune shift is:

$$\xi_x \;= \frac{r_e}{2\,\pi\,\gamma\,e\,f_{rev}} \cdot \frac{i_b}{\epsilon_x}$$

At the beginning of a fill with bunch currents of 500 μA and standard 1991 conditions (horizontal emittance $\epsilon_x =$ 36 nm and 45.625 GeV beam energy) we get $\xi_x = 0.04$. This is rather big and may substantially reduce the choice of good tune values. The vertical beam-beam parameter depends on β_y^* and can be calculated from the observed luminosity according to :

$$\xi_y \;= 2\,e\,r_e \cdot \frac{\beta_y^*}{\gamma} \cdot \frac{L}{I}$$

At high currents, the luminosity varies usually as $L \propto 1/I$. This corresponds to a constant value of ξ_y and indicates operation at the beam–beam limit. Fig. 2 illustrates the low beam–beam limit of on average $\xi_y \approx 0.015$ for 1990, that led to a change in optics from 71/77 to 70/76 in 1991. With this new optics, Fig. 3 shows that the beam–beam tune shift parameter ξ_y was significantly higher with typically $\xi_y \approx 0.02$ to 0.025 and in some cases up to $\xi_y = 0.03$. Early fills in 1991 had $\beta_y^* \approx 7.5$ cm. After a recalibration of the low-β superconducting magnets, LEP was run with $\beta_y^* \approx 4$ cm. Due to the lower β-value, the luminosity increased but Fig. 3 reveals, that the beam–beam limit was generally lower than before. The following period had generally $\beta_y^* = 5$ cm. It contains some fills with quite high ξ_y values. The last period corresponds to fills with combined ramp and squeeze to $\beta_y^* = 4.3$ and 5 cm.

The studies of ξ_y based on luminosity led to a number of observations:

- the beam–beam limit was improved from 1990 to 1991 but is still a major limitation
- the beam–beam limit is reached earlier for lower values of β_y^*
- strong beam–beam coupling led to coherent oscillations and bad lifetimes, which was eliminated by increasing the chromaticity.

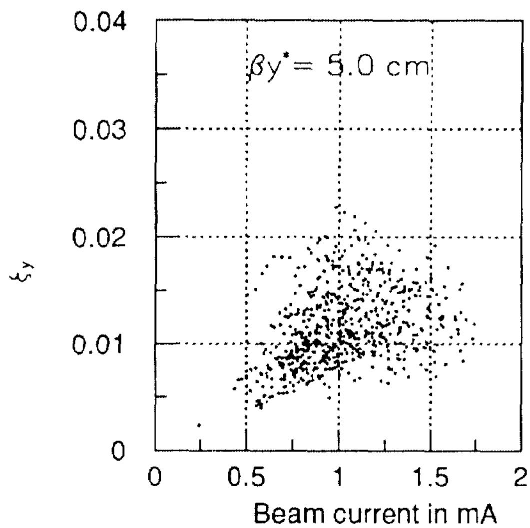

Figure 2: ξ_y dependence on beam current for the later fills in 1990 with $\beta^* = 5$ cm.

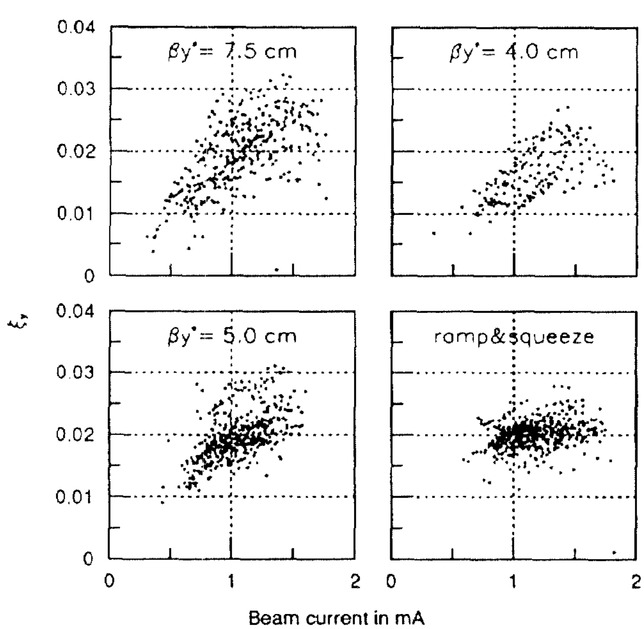

Figure 3: ξ_y dependence on beam current for all fills in 1991, subdivided in 4 sub-periods

Recent calculations have shown that, at least for the horizontal plane, these instabilities are driven by "errors" in the phase advance per collision point [2].

Fig. 4 shows the tune diagram of the 70/76 optics. Reso-

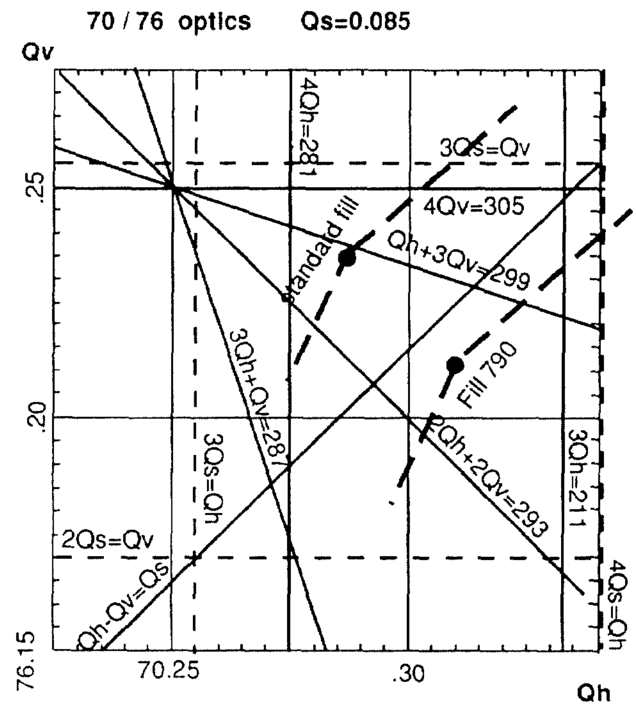

Figure 4: Tune diagram

nances up to fourth order have been included. Incoherent tunes in physics towards the end of the 1991 running were typically Qh=70.285 and Qv=76.235 . The coherent tune shift and the linear beam-beam tune shift are shown as thick, dashed lines. It has been observed that the beam-beam tune shift depends on the working point. Fill 790 for example produced a high beam-beam limit ($\xi_y \approx 0.03$) and it is interesting to note, that this coincides with rather nonstandard tunes (incoherent Qh=70.32, Qv=76.22, see Fig. 4). In future, LEP will be equipped with a facility to perform two-dimensional tune scans with fast logging of beam-size, lifetime, and background level at the experiments. The Q-meter will be upgraded to measure separately the 0 and π beam-beam modes. It is planned to display recent and actual performance in terms of ξ_y in the control room to guide systematic operational optimization.

4 REFERENCES

[1] S.Myers, Nucl. Instrum. Methods 211 ; p.263-282 (1983)

[2] E.Keil, LEP Perf. Note 82 (March 1991) and personal communication.