EXPERIENCE WITH BUNCH TRAINS IN LEP

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Abstract

Since 1995 LEP is operated with the new bunch train scheme. This scheme allows head-on collisions of four trains of up to four bunches within a train. The first experience with this new scheme and the problems encountered during the commissioning and the operation are reviewed and discussed. The performance of LEP and the results from dedicated experiments are shown and compared with expectations. The modifications and improvements to allow a successful operation at LEP2 energies are discussed and the performance at energies above 80 GeV is presented.

1 INTRODUCTION

The bunch train scheme for LEP was developed in 1994 [1, 2, 3], and then commissioned operationally in 1995 [4, 5, 6]. The two motivating factors for the scheme were:

- To increase the luminosity at Z° energies by increasing the number of bunches
- To raise the maximum current per bunch in 8 bunches per beam for operation at W energies.

The 8 bunch pretzel scheme [7, 8] was limited, at injection energy, to bunch currents significantly less than the expected 1mA. For operation at 45 GeV this limitation was not a problem since the beam-beam effect limits the bunch current to around 350 μA, which is easily attainable at injection energy with pretzel. However at higher energies, it is desirable to collide much larger intensities and this limitation becomes a problem. It follows that a new scheme should be flexible enough to permit an optimization of the number of bunches and bunch intensity, depending on the constraints and requirements.

The plan was to operate LEP in 1995 with four equidistant trains of bunches in each beam. The number of bunches per train is determined by the maximum length of the train, limited by the separation scheme and experimental constraints [5]. Simultaneously, the scheme was optimized and modified for running at LEP2 energies where eight bunches per beam and higher intensities per bunch were envisaged.

2 CONFIGURATION IN 1995

The 1995 bunch train scheme in LEP used electrostatic separators to provide extended local separation bumps around the interaction points (IP) such that: a) trains of up to four bunches separated by 87 λ_{RF} could be accommodated; b) all bunches in the counter- rotating e$^+$ and e$^-$ beams were separated at all encounters at injection energy and during the energy ramp; c) bunches in the counter-rotating e$^+$ and e$^-$ beams were separated at all parasitic encounters at physics energy; d) collisions could take place between e$^+$ and e$^-$ bunches at the four experimental IPs; e) a vertical 'vernier' bump could be superimposed at these points to allow adjustment of the collision for luminosity optimisation. In each such pit six separators are necessary, since the beams need to be brought into collision at the IP while remaining separated at the parasitic encounters, essentially creating a closed electrostatic 3 ”corrector” bump on each side of the IP. The small closed vernier bump was superimposed using two of the separator pairs.

Each of the odd (non-experimental) pits was equipped with four electrostatic separators, to create an extended bunch train bump which separated all e$^+$ and e$^-$ bunches [2, 6].

The direction of the separation bumps can be chosen freely but since some of the side effects of the bumps, (e.g. dispersion and orbit effects, see later section), can accumulate or cancel depending on the relative direction of the orbit distortion, the directions of the separation bumps were chosen to minimize these effects by a partial compensation.

3 SIDE EFFECTS AND BEAM DYNAMICS

3.1 Vertical dispersion

The vertical separation bumps induce a residual vertical dispersion proportional to the bump amplitude which must be kept as small as possible to avoid an increase of the vertical emittance or the excitation of synchro-betatron resonances in the RF cavities. An insufficient separation however, would lead to other effects, i.e. large beam-beam tune shifts and beam-beam induced orbit effects. This would result in low life-times and reduced luminosity. A compromise has to be found to meet all requirements simultaneously.

3.2 Effects from parasitic beam-beam interactions

Further insight into the side effects of the parasitic encounters can be gained by a first-order calculation, starting with the vertical orbits caused by the electrostatic separator bumps. The vertical orbit kick, $\Delta y'$, the horizontal and vertical beam-beam tune shifts, ξ_x and ξ_y, at a parasitic encounter are given by:

$$\Delta y' = -\frac{2Nr_{\mathrm{e}}}{\gamma d} \qquad \xi_x = \frac{Nr_{\mathrm{e}}\beta_x}{2\pi\gamma d^2} \qquad \xi_y = -\frac{Nr_{\mathrm{e}}\beta_y}{2\pi\gamma d^2} \qquad (1)$$

The separation between the beams at the parasitic encounter is d. It is assumed that the vertical r.m.s. beam radius is much smaller than the separation at the parasitic encounter, $\sigma_y \ll d$; N is the intensity of the opposite bunch, r_{e} is the classical electron radius, and γ is the usual relativistic factor. Any vertical orbit kick $\Delta y'$ causes a vertical orbit distortion y and a vertical orbit slope y' at any observation point around LEP which are given by the standard equations for the closed orbit and its slope. The closed orbit position and slope of a bunch are obtained by adding the contributions of all parasitic encounters with the bunches of the counter-rotating beam.

In general, different bunches in different trains meet the bunches of the opposite beam at different parasitic encounters. Therefore, different bunches travel on different vertical orbits and have different vertical slopes around LEP. Hence, different vertical collision offsets δy and different slopes $\delta y'$ exist between any two bunches colliding at the head-on interaction points. From symmetry arguments it is evident that, for an ideal machine without imperfections and equal bunch populations, the first bunch of a train has an orbit offset of the same magnitude and opposite sign as the last bunch of the equivalent counter-rotating bunch train. Similar arguments hold for each bunch of a train, resulting in an asymmetric orbit for the bunches along a train. It is easy to remove the average vertical offset by vernier adjustments, but it is impossible to remove the spread in the vertical offset between the bunches. For trains of only two bunches the above mentioned symmetry allows a vernier adjustment to collide both bunches of a train head on, although not on the same orbit.

Not only at the interaction point the orbit of a bunch is changed, the separation at a parasitic encounter is also affected and such a change of separation is not taken into account in the perturbative approach. A self consistent treatment of the problem becomes necessary.

3.3 Self consistent calculation

The first-order calculation mentioned does not include the consequences of the beam-beam interaction at the parasitic encounters. These effects are included in a self consistent computation which is embedded in a computer program `train`[10]. It finds the individual closed orbits of all bunches, as well as their vertical dispersion, tunes and chromaticities. The understanding and evaluation of the side effects via the self consistent calculation was important in understanding some of the limitations of the scheme. The comparison is made for bunch trains of three bunches per train since most of the time LEP was operated with such trains and experimental data is available.

3.3.1 Self consistent orbits

Tab. 1 shows the results of calculations of the separation s_y at the collision point in μm for the three bunches, labelled a, b and c in a typical bunch train in the even-numbered pits. The vertical separation s_y is symmetrical between the leading and trailing bunches in a train as expected. The measurement of the vertical separation between bunches in a train is a by-product of the luminosity optimisation by vernier scans. Fig. 1 shows the results of a typical scan. The difference between the optimal position for families a, b and c gives a measure of the shape of the trains and the width of the scan a measure of the vertical beam size which is significantly larger than the separation between the bunches. A rather good agreement between the calculated and measured results was found [6].

Table 1: Self consistent results for the separation s_y in μm for the three bunches in a train. The bunch current is $I = 0.25$ mA, the beam energy is $E = 45.6$ GeV.

Bunch	IP2	IP4	IP6	IP8
a	1.42	-1.59	1.82	.15
b	.32	.07	.61	2.09
c	1.42	-1.59	1.82	.15

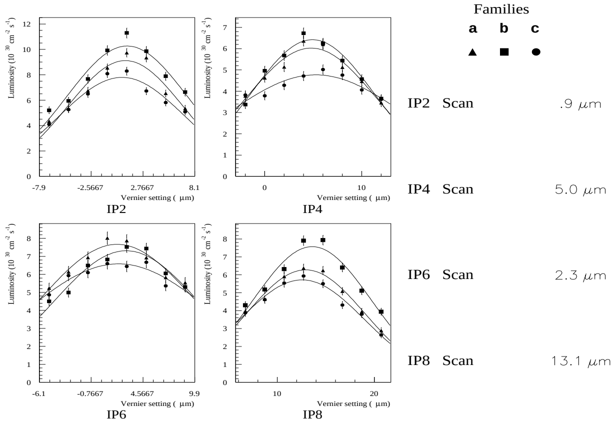

Figure 1: Vertical scans to optimize luminosity and to measure individual orbits

3.3.2 Tune and chromaticity splits

Similar differences between the bunches within a train exist for the tunes, the chromaticities and the dispersion. Typically one finds in the calculation splits up to 0.02 for the fractional part of the tune for bunch currents of 0.5 mA. The chromaticity spread can reach values up to $\Delta Q' \approx 1.0$. These calculations have been confirmed by measurements [6].

4 PERFORMANCE

4.1 Life time

In the original design it was foreseen to operate LEP with four bunches per train, i.e. each individual bunch having three parasitic encounters at each interaction region. The typical separation d at the three encounters in an even insertion are shown in Tab.2. Also shown are the calculated cor-

Table 2: Separation and normalized beam-beam tune shift for parasitic encounters

Encounter	Separation	ξ_x/ξ_y [10^{-3}]
1	10-12 mm	2.7/1.0
2	15-20 mm	0.3/1.5
3	5-7 mm	1.1/7.5

responding horizontal and vertical beam-beam tune shifts at 45.6 GeV and for 0.5 mA bunch current. It can be observed that the encounter farthest from the interaction point experiences a much larger vertical shift, caused by the significantly smaller separation [6]. During the running period when LEP was operated with four bunches per train, frequent life time problems were experienced for the bunches corresponding to this close encounter. As a consequence, it was decided to abandon the fourth bunch and continue the operation with three bunches per train, thus avoiding the encounter with the smallest separation. Furthermore, since the contribution of the 4th bunch to the spreads of the tunes and chromaticities is large, the overall spreads were also reduced. The machine was much easier to operate with these shorter trains and the life-time of all remaining bunches was acceptable [6].

4.2 Luminosity and beam-beam tune shift

When LEP was operated with three bunches per train, the luminosity was not fully up to the expectations and particularly the beam-beam tune shift achieved was lower than was hoped for. Values between 0.025 and 0.030 were the best found during the year. This should be compared with tune shifts of 0.03 to 0.04 regularly obtained with four bunches and the Pretzel scheme with 8 bunches, and with best values of around $\xi_y \approx 0.045$.

It was already demonstrated (Fig.1 and Tab.1) that with 3 bunches per train the bunches do not collide head on. It was believed that the lower beam-beam tune shift was caused by the offset collison. In a dedicated a run with only two bunches per train where all bunches can be collided head on, the beam-beam tune shift quickly reached values above 0.040 with a maximum at 0.045.

5 EXPERIENCE AT LEP2

5.1 Configuration in 1996

Unlike LEP running at 45.6 GeV, LEP2 is not beam-beam limited and it is advantageous to concentrate the available intensity into fewer bunches. While the aim at LEP1 was to increase the number of bunches the main issue at higher energies is to remove the intensity limits at injection and run with a smaller number of bunches. The original scheme was designed that it could operate with any number of bunches between one and the maximum of four per train and the bunch spacing was kept flexible to optimize it for the number of bunches, however fulfilling the constraints dictated by the hardware. For the first runs of LEP2 in 1996, no hardware modifications were necessary on the separation scheme but the bunch spacing was increased to minimize the residual beam-beam effects from unwanted parasitic beam-beam encounters [9]. The chosen spacing of 118 λ_{RF} is compatible with the existing longitudinal feedback system and has a minimum impact on the performance of the orbit measurement system.

5.2 Luminosity and intensity

In 1996 LEP was run at two energies: 80.5 and 86.0 GeV. During most of the year, the total current was limited to rather low values due to RF considerations and therefore the machine was operated with single bunch trains, i.e. four on four bunches. Furthermore, several low emittance lattices were tried [11] with varying success. However a few runs were made with trains of two bunches and the results were very promising. The beam-beam tune shift achieved was the same as for single bunches at equivalent bunch intensities and the resulting luminosity was as expected. The total current was always limited due to the commissioning of the large LEP2 RF system.

In a dedicated experiment [12] the maximum intensity at injection was studied for different RF configurations and no bunch train related problems were found up to intensities above 0.550 mA per bunch, where the intensity could not be further increased due to RF limitations. This is a very promising result for a good luminosity in future runs.

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