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Report of the 1995 Bunch Train Study Group

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Abstract

In order to raise the luminosity LEP was operated in 1995 with four equidistant trains of bunches in each beam, instead of the usual four or eight single bunches. Each train consisted of up to four bunches. The bunch spacing was about 74 m. A comparison is made between the plans and expectations in the 1994 Bunch Train Report, and the actual implementation and observations in 1995. The observations made during machine development sessions and during routine operation for physics are discussed. The effects of the scheme on the background in the LEP experiments are analysed. The performance of LEP equipment, in particular of beam instrumentation, electrostatic separators, and the RF systems is presented. The plans for running LEP with bunch trains in 1996 are briefly outlined.

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1 Summary

In the winter shutdown 1994/1995 the majority of hardware modifications were completed and the new mode of operation was commissioned successfully since the 1995 startup. During the course of the shutdown and following operational experience several small changes were made to the project as it had been perceived at the end of 1994[1]. These changes and the new understanding of performance with bunch trains are summarized.

1.1 Physics Goals for 1995

At the start of 1995 it was not clear whether the main goal in 1995 would be to significantly improve the statistics by running on-peak or to reduce the errors on the width of the Z by performing another energy scan. A key issue for the energy scan was the side effects of bunch trains and most notably a monochromatisation effect resulting from the presence of dispersion at the IP together with vertical orbit offsets. Following simulations and analyses of the probable errors it was finally decided to perform an energy scan with a target integrated luminosity of 10 pb^{-1} on each of the off-peak points. At the same time, a major goal for LEP in 1995 was the commissioning of substantial parts of the new superconducting RF system. Additional RF modules were installed during the June and October technical stops and from June onwards operation had to be adapted to allow for this new scenario.

1.2 Changes to the Machine Layout and Optics for 1995

LEP had been partially modified during the latter technical stops in 1994 so that tests could be made using two trains of up to four bunches, colliding in Pits 4 and 8. During the long shutdown the major steps remaining were the installation of additional separators in Pits 2 and 6, moving the outer separators in all of the odd pits and converting half of the pretzel sextupoles for bunch train operation.

As a result of observations during the 1994 tests it was decided to move at least some of the skew quadrupoles outside the bunch train bump. It was finally agreed to move all three (QT2, QT3 and QT4) to new locations beyond the outer separator.

It was hoped that a new optics configuration would improve the background conditions for the experiments but a detailed analysis of the side effects of bunch trains led to this optics being abandoned. The 1994 optics was re-matched to account for the new machine layout and was used throughout 1995.

1.3 Machine Development

In order to establish a baseline for the intensity limit measurements, the single beam limit was first measured. It was found that although this was lower than in previous years it was compatible with the changed impedance budget.

Multi-bunch beam breakup (MBBU) is a well-known phenomenon in linacs in which oscillations of a leading bunch are fed back to following bunches in a resonant manner through the wake fields. Theory predicts that large orbit offsets in the RF cavities should increase MBBU but the oscillation amplitudes did not change significantly when the bunch train bump was applied. Measurements demonstrated that in a train of three bunches the second bunch (b) had much larger oscillations than the leading bunch (a) whilst the third bunch (c) had smaller oscillations than the second. In the case of two bunches per train the second bunch had much larger oscillations. It is thought that these measurements are still consistent with a manifestation of MBBU with the wakes of the first and second bunch interacting destructively with the third. At the intensity levels reached in LEP in 1995 MBBU was not seen to be a limiting factor.

From the experiments on bump amplitude it was concluded that the effect on the single beam limit was small. The first attempt to reach the two beam instensity limit with bunch trains demonstrated that the limit was similar to that which had been achieved with the pretzel scheme. It was also demonstrated that a reduction in the bump amplitude to 80% of its nominal amplitude had no effect on the current limit.

The beam-beam tune shift achieved during operation was lower than expected. Investigations with a single bunch per train (and therefore collisions only in the even pits) showed that the bumps had little effect on the tune shifts. It proved difficult to push the beam-beam tune shift to high levels when using three bunches per train, but in experiments with two bunches per train tune shifts as high as those achieved with the pretzel scheme were possible.

1.4 Operation

A totally new way of running the machine had to be mastered by the operation team and new methods of optimisation had to be developed. These concerned not just luminosity, but also background and radiation. The process was a gradual one in which the number of bunches per train was increased up to the maximum of four. It was felt within the operations group that the bunch train scheme was easier to control than pretzel although the maximum number of bunches per train which could be comfortably handled was three.

Operation with bunch trains pushed key equipment, such as separators, to new limits, forcing the understanding of their performance up a steep learning curve.

The theoretical and practical understanding of the many side effects that arise from colliding bunch trains, in particular the effects of the parasitic encounters, took some time to obtain. However, a radically new way of running LEP was commissioned successfully. It was a challenge to the equipment groups, beam instrumentation, operations, accelerator physicists and management.

1.5 Background

The vertical bumps used to separate bunch trains in the experimental insertions generate particle background at the experiments. Detailed Monte Carlo simulations, which were confirmed by measurements, led to the definition of machine settings which minimised the additional background.

The additional large number of synchrotron radiation photons which are radiated from the quadrupolar fields along the bump can be prevented from reaching the detectors. This is achieved by limiting the bump amplitudes of the incoming beams, at the crest of the bump in QS4, below a threshold of 9 to 10mm. This condition was fulfilled for physics runs in 1995 by using 100% of the nominal bumps in Pits 4 and 8 and 70% of the nominal bumps in Pits 2 and 6. Fine tuning was done by superimposing small asymmetric magnetic bumps on the electrostatic bumps when necessary.

The OPAL luminosity detectors were disturbed by a very specific background component which was coming from off-energy bremsstrahlung particles. In order to suppress this, it was necessary to close the nearest vertical collimator to an aperture of $< \pm 30$mm as well as limiting the bump amplitude in QS4. In order to close these collimators it was necessary to reduce the vertical aperture limits from $30\sigma_v$ to $26\sigma_v$. In these conditions OPAL was able to achieve the precision required for the energy scan with their luminosity measurement.

1.6 Hardware Systems

1.6.1 BEAM INSTRUMENTATION

All of the modifications to the instrumentation required to run with bunch trains were successfully completed for 1995 and the performance throughout the year was very good.

The bunch current transformers worked well using the fast-sampling oscilloscopes which allowed measurement of single bunch currents. The new bunch current equaliser is based on these, and is indispensable for filling the machine.

Improvements to the BOM system for 1996 include better triggering for position measurements of individual bunches and the installation of wide band electronics on 32 more BPMs. It was demonstrated in 1995 that it will be possible make a rapid optimisation of luminosity by scanning the beam separation whilst measuring the orbit distortion due to the beam-beam effect – this will be implemented. It has been decided to convert 4 more narrow band BPMs on either side of the experiments in order to give more complete information in the region of QS5 to QS9.

The synchrotron radiation telescopes (BEUV) were able to measure beam sizes of individual bunches in a train. The absolute calibration of the instrument is checked about once per year but this calibration is only as good as the knowledge of the dispersion and β- functions at the instrument. It has been agreed that some changes are required in the control system so that more realistic information is available at all times.

The polarimeters worked well throughout 1995 but suffered from the synchrotron radiation produced by the vertical separation bump in Pit 1. This radiation damaged the mirror and caused outgassing of the supporting structure. These problems will be resolved by replacing the mirror with a metallic one and removing the coating from the support structure.

1.6.2 SEPARATORS

Operating with bunch trains requires that the trains are separated at all times in the even pits, which implies that all 40 separators are operated at high voltage during physics, thereby increasing the probability of sparking. In Pit 3 repeated sparking was observed but studies failed to reveal the cause. It was found that the sparking could be suppressed by operating the separators with positive high voltage only.

During the high energy run the synchrotron radiation had a critical energy of around 230 keV, compared to 70 keV for 45 GeV operation. Only one spark was recorded during this run and it did not cause any beam loss. During most of this run the separators in the even pits were only run at 20% of their nominal fields but all of the separators in the odd pits were powered normally. Radiation measurements made during the high energy run show a correlation with the areas where sparking was a problem.

1.6.3 RADIO FREQUENCY SYSTEM

Operation with bunch trains allowed high currents to be accumulated and this in turn facilitated the debugging of the new superconducting RF systems. One of the major concerns when designing the bunch train scheme was the possibility of higher order mode (HOM) power coming from the bunches in a train causing full coherent addition of the fields in a cavity. Measurements in 1995 have not shown this to be the case but in some cases the extracted HOM power exceeded that which would be obtained if the powers were added.

The longitudinal feedback system was set up to run with a fixed bunch spacing of 87 or 174 λ_{RF} during 1995, which was the optimum for four bunches per train. For a different spacing the phase at the feedback frequency will be different for each bunch in a train and therefore it would not necessarily work. It is planned to run with only 2 bunches per train in 1996 and the optimum spacing is around 124 λ_{RF}. It has been shown that a spacing of 118 λ_{RF} will only cause a small phase error and the performance of the feedback system should be adequate. The modifications to the longitudinal feedback system in order to make it work with the closely spaced bunches in trains resulted in some voltage loss but this has been overcome by operating the system in pulsed mode.

The transverse feedback system was modified to run with fixed amplitude pulses, using one of the kickers for bunches a and c, and the other for bunches b and d. The system performed very well in this mode, made accumulation easier and prevented beam losses at the start of the ramp. The system was also often used in physics and helped to prevent background bursts in the experiments. The change to a longer spacing for 1996 means that the system can be re-optimised and the same kicker can be used for both bunches. In this new mode the maximum damping rate will be a factor of 3 higher than in 1995 for the same beam energy.

1.7 Bunch Trains in 1996 and beyond

Running at higher energies implies that we will have smaller separations, fewer bunches per train, larger energy sawtooth and stronger effects from RF asymmetries. In the long term the RF power available will limit the total current and in order to optimise luminosity it will be desirable to put the maximum current in the smallest number of bunches. In 1996 it has been decided that the beam current will be kept low during early running as a cautionary measure to protect the new RF equipment. During this initial phase LEP will be operated with four bunches and after the current limit has been raised, with eight bunches.

The side effects from bunch trains are driven by the parasitic encounters and although the beam-beam tune shift scales as E^{-1}, the dependence on the separation is δ^{-2} and therefore the tune shift will increase when we move to higher energies. Furthermore, higher bunch currents will drive the tune shift to even higher levels. However, it is believed that the stronger damping at higher energies will compensate this effect to some extent.

When operating with only two bunches per train, the bunches can be collided head-on and thus the beam-beam induced orbit effects will not be a problem. Running with two bunches per train also offers the possibility to minimise the parasitic beam-beam effects by changing the bunch spacing. It has been shown that a spacing of between 115 and 160 λ_{RF} would be a good choice. Vertical dispersion is another troublesome effect which will be reduced when running at higher energies because it is driven by the bump amplitude.

The strongly increased synchrotron radiation associated with running at higher energies leads to a significant sawtooth in the horizontal orbit and an asymmetric energy distribution around the ring. This effect can lead to a non-closure of the separation bumps which is enhanced when the RF distribution becomes more unbalanced due to RF trips. Simulations indicate that the likely vertical separation caused by this can be corrected with the separators. There is also an effect in the horizontal plane but this is expected to be relatively small.

Because the maximum achievable separation at 90 GeV is 5.5 mm, which is well below the critical amplitude, no additional photon or off-energy background problems are expected with the bunch train scheme for LEP2.

1.8 Conclusion

1995 was a difficult year for operation because the machine was very different and had to be run in a completely new way. The modifications to the hardware were completed on time, even the additional work of moving skew quadrupoles. The hardware performed very well although many changes to the way in which it was used were necessary in order to optimise performance. Although the luminosity yield was lower than had been hoped for, the physics goals for the year were met and the overall expectations for operating LEP2 with bunch trains are high.

2 Implementation

In this section, we describe the main differences between the bunch train scheme as planned and described in [1] and the actual implementation in the course of 1995, under the following headings: (i) Lattice, (ii) Bump amplitudes, (iii) Number of bunches, (iv) Coupling and solenoid compensation.

2.1 Lattice

The even pits were re-matched, in three stages:

1. A new configuration, MP, was developed [2] in which the excitations of both the upright and skew quadrupoles were changed. This configuration had smaller β-functions in the RF sections than the LP configuration, and a perfect solenoid compensation. It was abandoned because the vertical beam-beam kicks at the parasitic collision points caused a vertical crossing angle for trains with four bunches which was considered unacceptable [3].
2. We then returned to the LP configuration which had been used for the 1994 bunch train tests [4], and had smaller vertical crossing angles than the MP configuration, and adapted it to the new quadrupole positions [5]. However, this LPv3 configuration did not have a perfect solenoid compensation, as discussed in Section 2.4.
3. This configuration was modified several times in order to reduce the vertical amplitude function β_y in particular in QS4 and thus the background in the experiments. We commissioned LEP after the 1994/95 shutdown with the LPv6 configuration which had even more serious problems with solenoid compensation, as discussed in Section 2.4.

2.2 Bump Amplitudes

The bump amplitudes actually used in physics at 45.6 GeV were smaller than those planned. Tab. 1 shows the scaling factors. The bump amplitudes in pits 2 and 6 were reduced in order to limit the photon background originating at the quadrupoles in the bumps, as discussed in Chapter 5. The bump amplitudes in the odd pits were reduced because of a sparking problem in Pit 3, discussed in Chapter 7. We decided to reduce the bump amplitude also in the other odd pits in order to preserve the cancellation of various side effects. For their calculation, we used the first-order perturbation theory embedded in the `orbit9` program [6], and a new post-processor `train` for MAD [7] which finds the individual closed orbits of all electron and positron bunches in LEP, and computes the side effects on these orbits in a truly self-consistent manner [8]. The results for the side effects at the bump amplitudes in Tab. 1 are displayed in [9] in the form of tables of the separated beam-beam tune shifts, the tunes and

Table 1: Scaling factors for bunch train bumps

Pit	1	2	3	4	5	6	7	8
Factor	8/9	0.7	8/9	1	8/9	0.7	8/9	1

chromaticities, and of the vertical offsets and separations, the vertical slopes and crossing angles, the vertical dispersion, the CM energy shifts [10] and the relative luminosities in the even pits.

2.3 Number of Bunches

After some initial attempts to inject trains of four bunches into LEP, which were not very successful as discussed in Chapters 3 and 4, LEP was operated with trains of three bunches for most of the remainder of 1995. The bunch spacing was kept at $s = 87\lambda_{\rm RF}$ because the longitudinal feedback system only operated at this value although it is not the optimum for trains of three bunches.

2.4 Coupling and Solenoid Compensation

In the 1994 design [1], most of the skew quadrupoles which compensate the solenoids in the LEP detectors were inside the vertical bumps excited by the electrostatic separators. The two most noticeable consequences were a horizontal emittance blowup, related to the vertical bumps and the solenoid compensation, which was never explained satisfactorily, and a horizontal crossing angle in the even pits [1]. In order to avoid them, the skew quadrupoles labelled QT2, QT3 and QT4 were rearranged in the 1994/95 shutdown close to the QS7, QS8 and QS9 quadrupoles, beyond the separators which close the bumps. The skew quadrupoles labelled QT1 remain close to the QS2 quadrupoles, where the two beams are not separated during colliding-beam physics runs.

The LP configurations have the drawback that the solenoid compensation intended to fully decouple the horizontal and vertical betatron oscillations at the IP in Pits 4 and 8 is not perfect because the skew quadrupole QT4 close to QS9 is not strong enough. In the LPv6 configuration, the QT4 quadrupole in Pit 4 should be 61%, and that in Pit 8 27% stronger. In the LPv3 configuration, the strengths of QT4 are smaller. No mechanism has been found in simulations [11] of the LPv6 configuration which relates the actual coupling compensation to the observed beam sizes. However, it was observed during MD [12] that the vertical beam size was sensitive to the solenoid compensation scheme applied.

3 Results of Machine Development

During 1995, dedicated bunch train machine development sessions were used to study various bunch train configurations and limitations such as intensity limits at injection [13], effects of bunch train bumps, beam-beam tune shifts and beam breakup.

3.1 Bunch Intensity Limitations at 20 GeV

3.1.1 SINGLE BEAM LIMIT

Since 1993, the single beam limit has decreased. Consequently, the single beam limit in the bunch train configuration was checked first. The single beam limit in the flat machine, i.e without any bunch train bump, was established [14], and it was confirmed that from 1993 to 1995 it decreased by about 10%. This is consistent with an increase of the LEP impedance of about 8% from 1993 to 1995 [15, 16].

The effect of forming trains with a single beam was then addressed. With one train of two bunches a and c, [14], the intensity accumulated into the first bunch (a) of the train was close to the single beam limit. However the intensity accumulated in the second bunch (c) was lower by about 10 to 15% than the single beam limit. In both cases, it was clearly observed that when the bunch intensity reached 500 μA , bunch c started to lose intensity each time bunch a was injected. This was the real limitation in accumulating more intensity and no real cure could be found.

The effects of bunch train bumps on the intensity limit were studied during the same experiment [14], using one train of two bunches of positrons, and with the bunch train bumps switched on in the even pits only. Accumulation into the bunches a and c showed that the effect of the bunch train bumps on the single beam limit was very small. In another experiment [17], this time done with a single bunch single beam, the bunch train bumps were switched on in all points and it was observed that the single beam limit was lowered by at most 10%. From these experiments, it was concluded that the effect of the bunch train bumps on the single beam limit was small.

3.1.2 MULTI-BUNCH BEAM BREAK-UP

Multi-bunch beam break-up (MBBU) occurs in bunch trains and may lead to large oscillations and/or particle loss in later bunches [18, 19]. MBBU was studied in two MD runs, in particular by measuring the oscillations of individual bunches and their dependence on orbit separation [20]. With three bunches per train, the oscillation amplitude of the first bunch (a) was small but finite, always below 1 mm. The oscillation amplitudes of the second bunch (b) – at 87 λ_{RF} or about 75 m distance – were larger (up to 4 mm), while the amplitude of the third bunch (c) – at twice the distance from a – was somewhat smaller (1.5 mm). This could be explained if the wakes of bunch a and bunch b happen to interfere destructively, but more likely the large-amplitude oscillation of bunch b leads to sufficiently large frequency detuning that the resonant buildup of the oscillation of bunch c was disturbed.

With only two bunches per train, higher bunch currents could be reached and it was observed that the second bunch (c) still had considerably larger oscillation amplitudes, about 3 to 5 times larger that of the first one. This might explain the large background observed with bunch trains of high currents.

While measuring the effects of orbit separation in SC cavities, it was observed that the oscillation amplitudes of all bunches did NOT change significantly when the bump was applied, i.e. for a substantial vertical displacement of the orbits inside the SC cavities.

The transverse feedback did reduce the oscillation amplitudes, but the amplitudes of bunch b remained larger than 1 mm. Longitudinal bunch motion occurred, probably due to loss of Landau damping, and longitudinal feedback was needed to keep the bunches stable. Synchro-betatron resonances were difficult to avoid with such a large number of bunches, with slightly different tunes which split into a number of sidebands at higher current levels.

3.2 Two Beam Studies at 20 GeV

3.2.1 MAXIMUM INTENSITY WITH TWO DIFFERENT BUNCH TRAIN CONFIGURATIONS

In November 1994, installation of additional separators in IP4 and IP8 had permitted the first accumulation of two counterrotating beams [21]. In 1995, one experiment was dedicated to the comparison of the 1994 and 1995 results [14]. The intensities reached were found to be slightly lower than those found in the machine development in November 1994 but this could be explained by the higher synchrotron tune used in 1994. During the same experiment, no significant differences in the accumulated intensity were observed between a bunch configuration with collisions in 4 and 8 and a configuration with collisions in 2 and 6 [14].

3.2.2 EFFECT OF THE BUNCH SPACING ON THE ACCUMULATED INTENSITY

Injection into bunches (a,b) (87 λ_{RF}) was compared to injection into bunches (a,c) (174 λ_{RF}) [14]. With the bunches (a,b) no injection problems were observed with a current above 400 μA and it seemed significantly easier to reach 400 to 450 μA than with the (a,c) configuration. The injection was limited

by losses on the bunches not injected. The threshold where this occurs is slightly higher than when bunches a and c are injected. This might come from the fact that the bunch c has a smaller separation at the crossing points in the odd pits.
It was concluded that a configuration with bunches a and b seemed more favourable for filling than bunches a and c. It can be expected that for a bunch spacing optimized for a two bunch operation, the intensity limit can be pushed further.

3.2.3 RECORD INTENSITY WITH BUNCH TRAINS VS. PRETZEL

One important issue was to compare the bunch train scheme results with the pretzel scheme results, in terms of “record” intensity. Two beams of four trains of two bunches were injected [14]. The synchrotron tune was Q_s=0.098, there was no transverse feedback and the polarization wigglers were switched on. Accumulation into bunches a and b of each train gave an average intensity of:

$$< I > = 452\ \mu\text{A/bunch for e}^+ \text{ and } < I > = 365\ \mu\text{A/bunch for e}^-$$

The maximum intensity reached in the positron bunches was 495 μA. The injection was again limited by losses on the bunches not injected. These results were obtained during one single attempt. For comparison, the best results obtained with the pretzel scheme [22] were:

$$< I > = 440\ \mu\text{A/bunch for e}^+ \text{ and } < I > = 387\ \mu\text{A/bunch for e}^-$$

This was obtained with a synchrotron tune Q_s=0.097, the transverse feedback was switched on but no polarization wigglers were used.
It was concluded that the first attempt with bunch trains was similar to record pretzel intensity, under similar conditions.

3.2.4 EFFECT OF THE BUNCH TRAIN BUMP AMPLITUDE ON THE ACCUMULATED INTENSITY

Due to the side effects of the bunch train bumps, it is important to evaluate the minimum bunch train bump amplitude which still gives sufficient intensities. In 1994, it was shown that for one train of two bunches against one train of two bunches, 60% of the bump amplitude gave the same maximum intensity as for 100% [21].
In 1995, no dedicated experiments were done during injection to study the effects of the bunch train bumps on the intensity. A quick attempt was however done [14], and a reduction to 80% of the bump amplitude had no effect on the intensity. It was concluded that for trains of two bunches, the effect of reducing the bunch train bump amplitude is very minor, if any.
It was also observed that if bunches (a,c) were used, c was limited due to encounters in the odd points, and if (a,b) were used, b was limited due to encounters in the even points. These observations were confirmed in studies of the beam lifetime as a function of the bump amplitude [23, 24].

3.3 Beam-Beam Tune Shift Studies

During 1995, the beam-beam tune shift parameter measured during normal operation with bunch trains of three bunches per train was lower than expected and rarely exceeded ξ_y = 0.03. Extensive studies were performed to explain this observation and the parameters that affect the beam-beam tune shift were studied.

The first candidates which were suspected in the beam-beam tune shift reduction were the bunch train bumps. During one experiment [25] it was shown that with a single bunch per train and only collisions in the even points, the presence of the bunch train bumps had no immediate and drastic effect on the beam-beam tune shift although an optimization was easier without the bumps and an improvement was possible with some effort. It was also observed that the initial beam-beam tune shift was already higher than in normal operation.

In another experiment [12], another hypothesis was tested that the observed low tune shift was originating from unavoidable collision offsets when more than two bunches per train are used. After the vernier scan, the tune shift from the experiments was already significantly larger than the usual values observed in standard physics conditions with three bunches per train, indicating a potential for higher tune shifts in this configuration with four trains of two bunches.

Measurements of the beam-beam tune shift and its possible limit were performed, first with all bumps on and then with bumps in even points reduced to 50%. The average beam-beam tune shift from the two experiments which were taking data, together with the “best” tuneshift, i.e. the better of the two experiments, is plotted in Fig. 1.

Figure 1: Average (lower line) and best (upper line) beam-beam tune shift from the two experiments.

With all bumps at nominal values, and following orbit corrections and further optimization with coupling and emittance wigglers, tune shifts of about ξ_y = 0.036 were achieved, with potential for further improvement. The best value found using only the luminosity from one experiment was around ξ_y =0.038.

After the bumps in the even pits were reduced to 50% (a scenario which is expected for LEP2), no immediate gain was observed, but after a lengthy and steady optimization using coupling compensation, vernier scans, orbit and asymmetric dispersion bumps, an average beam-beam tune shift of up to ξ_y = 0.042 was measured, corresponding to an average luminosity of $15.1 \cdot 10^{30}$ cm^{-2} s^{-1} with a beam current of 3.6 mA. Using only the luminosity seen by one experiment a best value as large as ξ_y = 0.045 was obtained.

It was concluded that, in the configuration studied, beam-beam tune shifts as high as observed with the pretzel scheme in 1994 could be reached after careful optimization.

4 Results of Machine Operation

4.1 Overview of the Year

4.1.1 START-UP

After the cold-checkout LEP came up fairly smoothly and the first closed orbit was obtained on the 22nd April. Several issues relating to bunch trains and more general machine conditions were dealt with before the first physics run on the 3rd May. The first physics runs were performed with one bunch per train and with bunch train bumps reduced to 10%. Of note during the running in period:

- Radiation to the experiments at injection. It was proven that this could be effectively controlled by ensuring that the vertical injection trajectory was properly optimised, by reducing the bunch train bump amplitude, by using asymmetric magnetic bumps, and the use of vertical collimators near the interaction point (IP).
- Adjustment of the superconducting quadrupoles' calibration curves in order to equalise the measured β's at the IPs, a somewhat empirical process.
- Bunch train bump closure at 20 and 45 GeV. Corresponding separators either side of an IP are driven by the same generator. By adjusting the voltage ratio between the pairs of separators used to produce a bump, it is possible to minimise the non-closure of a given bump.
- Background. Much work was performed to understand and cure the background caused by the bunch train bumps, c.f. Chapter 5.

4.1.2 FIRST RUNNING PERIOD 6TH MAY - 25TH JUNE

Two bunches per train

On the 6th May the first physics run with two bunches (a & c) per train was performed with a total current of around 3 mA. Subsequently the machine was dogged by a number of problems which included persistent separator sparking in point 3 and on going concern about the non-closure of the separator bumps at both 20 and 45 GeV (more on this below).

Injection efficiency was generally low and the radiation produced seemed sensitive to the bump amplitudes in the odd points, particularly point 3. It eventually transpired that there was an aperture restriction either side of point 3, caused by misalignments of the vacuum chamber.

The log-book during this period reads like a litany of vernier scans, background spikes, poor lifetimes and coherent oscillations as operations struggled to master bunch train running. However, all was not doom and gloom: by the middle of May typical total currents were around 3.6 mA and beam-beam tune shifts were between 0.02 and 0.03. By the end of May the beam-beam tune shift was above 0.03 and over 4.5 mA was being collided. During this period the commissioning of the superconducting RF cavities started with attendant teething problems. The non-closure of the asymmetric bumps seemed to have been accepted as a fact of life by this stage.

It always takes time to bed the machine down and optimise it properly. It was clear that LEP was on it's way but had yet to reach optimal performance with two bunches per train. It was also clear, however, that the push had to be towards trains of four and LEP continued running with two bunches per train until June 18th when the first attempts at trains of three bunches were made.

By this stage the bunch currents at start of physics were around 300 μA/bunch ($\approx$ 5mA total), the peak luminosity was about $1.3 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and the beam-beam tune shift hovered around 0.03. The bunch train bumps in physics were at 64% of maximum in L3 and Opal, 80% in Aleph and Delphi.

Three bunches per train

As proof of principle a small number of fills were performed with three bunches per train. These attempts were reasonably successful with currents around 250 μA/bunch ($\approx$ 6mA total), peak luminosities of $1.2 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and beam-beam tune shifts of around 0.02.

Four bunches per train

Thus encouraged, trains of four bunches were attempted during the last week before the technical stop scheduled from June 26th. The polarisation wigglers were successfully commissioned and with their help 9 mA was accumulated. It proved possible to ramp and squeeze with four bunches per train without loss. However the first attempts at physics were foiled by sparks in IP2 and IP6 and other problems.

There was already an indication of something pathological: the lifetime of electron bunches a and d seemed to be poor in collision. Of nineteen attempts, three were lost at the start of the ramp, 6 were lost at the end of the squeeze (separator/orbit reload), 4 were lost during collision. 4 physics fills were performed with missing bunches, 2 with a full complement of 32 bunches. Thus it was that operations limped into the shutdown on 25th June.

Typical conditions when in physics with four bunches saw currents around 250 μA/bunch ($\approx$ 6mA total), peak luminosities of $1.5 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with beam-beam tune shifts around 0.02. These fills were performed with bunch train bumps at 100% of maximum.

In a little over a month and a half, operation with two bunches per train had been successfully proven and a lot of problems resolved. Most noticeable among these were: sparking, misalignments, radiation at injection, vernier scanning and QS0 calibration. Three bunches a train had been tried successfully, and the first dogged attempts with trains of four had been made.

4.1.3 SECOND RUNNING PERIOD 14TH JULY - 9TH OCTOBER

Physics was reestablished after the technical stop with initial runs with trains of one and of three bunches. Repeat tests on the asymmetric bumps showed that by this stage they were closed.

On the 18th July, attempts with trains of four bunches recommenced; 8 mA was successfully brought through the squeeze, but lost going into collision with a separator fault.

Several more attempts were made with four bunches per train, but the ramp and squeeze, although not impossible, was sensitive, bunch a of either beam being particularly susceptible to problems. In collision the lifetime of bunches which experienced the closest encounters of a parasitic kind were generally poor. The situation was exacerbated by the commissioning of new superconducting RF cavities at the same time. A strategic retreat to trains of three bunches was made on the 23rd July. Around this time the use of transverse and longitudinal feedback in physics started: this clearly helped stabilise physics running.

The rest of the running period was devoted to an energy scan. To facilitate this, the running conditions were bedded down to provide a stable framework for the painstaking process of the scan. The amplitude of the bunch train bumps were fixed at 70/100/70/100% of their maximum in points 2, 4, 6 and 8 respectively. Currents were limited somewhat below their maximum. Transverse feedback was in use during the ramp.

The fixed conditions allowed a slow, but steady, improvement in performance and by the end of August over 8 mA was being regularly brought up the ramp and through the squeeze. Beam-beam tune shifts were around 0.03 with typically initial luminosities of $1.7 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$: the bunch train scheme was at least equalling the best performance of pretzel [26]. Besides the normal operational frustrations the main bunch train related drawback was the continued background storms which appeared to be related to beam instabilities.

Things had settled down so much by the end of August, that the key question had become: “Why is the beam-beam tune-shift so low”. Recall that peaks of 0.045 had been achieved with pretzel, and steady running above 0.04 was not uncommon. All the usual tools of the operations’ twiddling trade were tried to no avail. This included a squeeze of the horizontal beta at the interaction points. This might have produced an improvement, but thorough re-optimisation at the reduced beta was not pursued. The ξ_y observations for bunch train operation with trains of three bunches [27] are shown in Fig. 2.

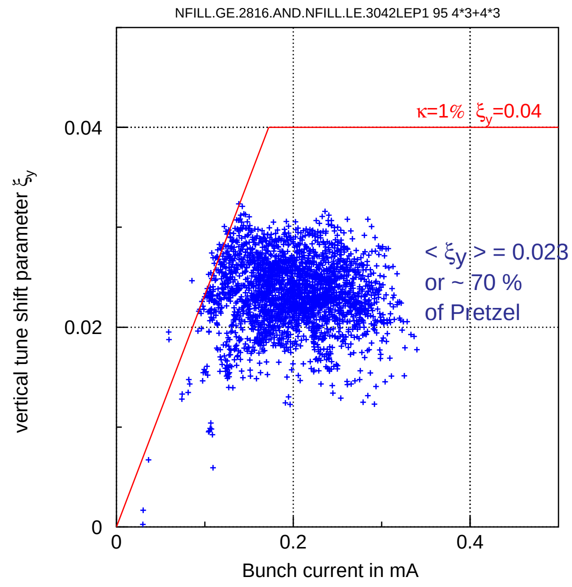


Figure 2: ξ_y observations for bunch train operation with 4x3+4x3 bunches.

Steady running continued through September with the tune splits corrected with the bunch train sextupoles, and dispersion measurements at the IP performed using vernier scans. The scan continued until the machine development period which started on 4th October, the machine development period was followed by high energy machine tests which signified the end of Z^0 running at LEP.

The bunch train scheme to this juncture has been a qualified success, a lot of effort had gone into operating LEP in a completely new mode, and a very reasonable performance secured. However, the effects of the parasitic encounters had led to the abandonment of four bunches per train, and the beam-beam tune-shifts with three bunches per train had stalled at around 0.03, presumably due to orbit offsets at the interaction point produced, again, by the parasitic encounters. The gradual mastering of the scheme is apparent in the luminosity production, see Fig. 3.

4.1.4 THE HIGH ENERGY RUN

Commissioning for high energy running began on October 27th, and within four days the first physics at 65 GeV took place. Because of the cautionary current limit imposed by the RF group, the high energy run took place with four bunches against four bunches with the amplitude of the bunch train bumps reduced initially to around 20%, and later to around 50%, of their maximum values. The attendant background conditions are described in Chapter 5, but were generally good.

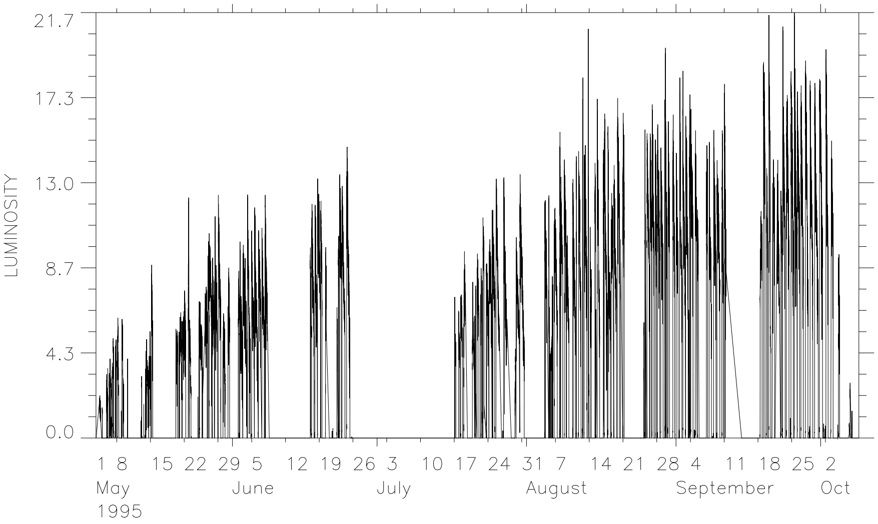


Figure 3: Luminosity through the 1995 Z^0 running period. The ordinate is in units of $10^{30}\text{cm}^{-2}\text{s}^{-1}$.)

The final run of the year was performed with 5.6 mA in trains of two bunches at 68 GeV. The bump amplitudes were set to 70/100/70/100% of the maximum in points 2, 4, 6 and 8 respectively. This was a big success producing peak luminosities of $3.4 \cdot 10^{31}\text{cm}^{-2}\text{s}^{-1}$, with clean background conditions. In another experiment which used trains of two bunches the beam-beam tune shift was raised above 0.04. In this scenario, with suitable optimisation, both bunches in a train can be collided without an offset [12].

4.2 Observations from Operations

4.2.1 NON-CLOSURE

There was initially some concern about non-closure of the bunch train bumps, which was visible in difference orbits. The r.m.s. of the vertical difference orbit (bumps suppressed) at 20 GeV was as high a 1 mm at the beginning of May. At 45 GeV the figure was typically 0.5 mm.

Two points should be made: firstly the bumps in 4 & 8 at 20 GeV were an almost perfect 3π bump, with no voltage on the internal separators, precluding adjustment of the closure by varying the ratio of internal and external voltages. Secondly, closure was checked point by point, with all other separators at standby. There turned out to be a floating 3 to 4 kV on the external separators when at standby, which certainly would have confused any corrections.

However, the situation was further clouded by the observation of non-closure of asymmetric bumps which were used to alleviate the experiments' background. Suffice to say that by the start of running period two, concern, and to some extent the non-closure, had abated. Operationally we learnt to live with an r.m.s. vertical difference of around 0.8 mm at 20 GeV, and a r.m.s. vertical difference of around 0.5 mm at 45 GeV.

Also of note was a curious and large r.m.s. horizontal difference at 20 GeV which reached 1.2 mm. This effect was subsequently explained by the discovery of a tilted superconducting quadrupole in pit 6 at the end of the year.

4.2.2 TUNE SPLITS

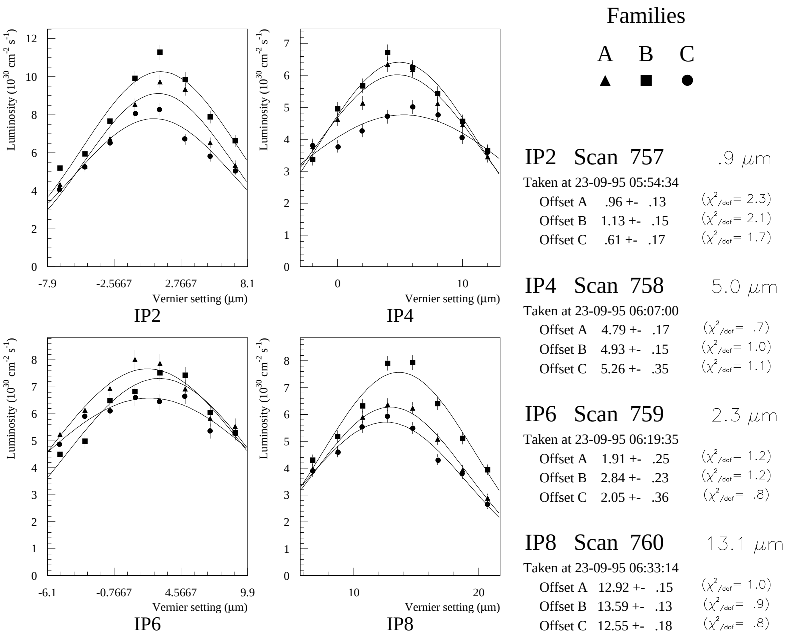
With three bunches per train there was a measured difference between electrons and positrons of 0.019 ± 0.006 horizontally and -0.0164 ± 0.006 vertically, while the tunes of b differed by $\approx .004$ from those of a and c. These agree, more or less, with the theoretical predictions [9].

4.2.3 BETA BEATING

At the start of the year the beta beating seemed improved after the QS0 adjustments and beating was below 20%. Similar values were obtained in subsequent measurements. For example on 15 May at 45 GeV with bumps fully on the beating was generally less than 20%. Again on the 29th May beating of 15-25% was seen with bumps at 80%. Associated phase advance measurements revealed small errors. At 20 GeV with bump train bumps the beating was around 12%. During a beam instrumentation cross calibration MD, measurements were made with and without bumps. There is evidence that the bunch train bumps increase the beating by 10% or so.

4.2.4 VERNIER SCANS

Standard operations' practice to ensure optimum collision was the use of an automated vernier scan. This was also used heavily during the energy scan to minimise the centre of mass energy shift in a given IP due to collision offsets. A typical on-line display is shown in Fig. 4. The ability to perform these scans was vital to the energy scan and the results have been carefully analysed [28].



IP2 Scan 757 .9 μm
Taken at 23-09-95 05:54:34
Offset A .96 +- .13 ($\chi^2/_{dof}$= 2.3)
Offset B 1.13 +- .15 ($\chi^2/_{dof}$= 2.1)
Offset C .61 +- .17 ($\chi^2/_{dof}$= 1.7)

IP4 Scan 758 5.0 μm
Taken at 23-09-95 06:07:00
Offset A 4.79 +- .17 ($\chi^2/_{dof}$= .7)
Offset B 4.93 +- .15 ($\chi^2/_{dof}$= 1.0)
Offset C 5.26 +- .35 ($\chi^2/_{dof}$= 1.1)

IP6 Scan 759 2.3 μm
Taken at 23-09-95 06:19:35
Offset A 1.91 +- .25 ($\chi^2/_{dof}$= 1.2)
Offset B 2.84 +- .23 ($\chi^2/_{dof}$= 1.2)
Offset C 2.05 +- .36 ($\chi^2/_{dof}$= .8)

IP8 Scan 760 13.1 μm
Taken at 23-09-95 06:33:14
Offset A 12.92 +- .15 ($\chi^2/_{dof}$= 1.0)
Offset B 13.59 +- .13 ($\chi^2/_{dof}$= .9)
Offset C 12.55 +- .18 ($\chi^2/_{dof}$= .8)

Figure 4: Typical on line display. The last vernier scans in each interaction point is displayed. The individual fit results and their χ^2 are indicated on the right, together with their weighted mean.

4.2.5 DISPERSION

Vertical dispersion was measured occasionally through the year to have typical r.m.s. values of 6 to 8 cm. There was some evidence of a dispersion split with a value of 5.1 cm being recorded for positrons versus 9.0 cm for electrons. Recall that magnetic errors cause vertical dispersion errors of the same sign for electrons and positrons while the separator bump causes vertical dispersion of opposite sign. The difference in dispersion at the interaction points was measured by performing vernier scans at different RF frequencies. Differences in the vertical dispersion of the beams of up to 3 to 4 mm where observed. Again the results are in approximate agreement with predictions [9].

4.2.6 HORIZONTAL MISCROSSINGS

Some evidence for horizontal miscrossings at the interaction points came from fits to difference orbits. Estimates of up to 40 μm were calculated [29]. The miscrossings appear to scale with bunch train bump amplitude. They are believed to have originated from the tilted SC quadrupole in pit 6.

5 Particle Background

Two types of beam-induced background to the experimental detectors are important in LEP: photons from synchrotron radiation (SR), mainly radiated in the straight section quadrupoles, and off-energy electrons and positrons, produced by beam-gas bremsstrahlung along the last part of the bending arcs and the straight sections. Both background types are influenced by the vertical separation bumps. The amount of additional photon and electron background as function of the bump amplitude has been carefully studied by Monte-Carlo simulation and has been compared with measurements [30, 31].

Radiation source	Radiated photons	
	no bump	full bump
QS11 to QS6	24	30
QS5 to QS3	11	324
QS1 and QS0	87	89
separators	0	28
total number	122	471

Figure 5: SR photon sources with and without separation bumps in IP6 (OPAL) for 45.6 GeV beams of 40 nm horizontal emittance. Photon rates are in units of 10^9 photons per 1 mA current in one bunch crossing (BX$\times$mA)

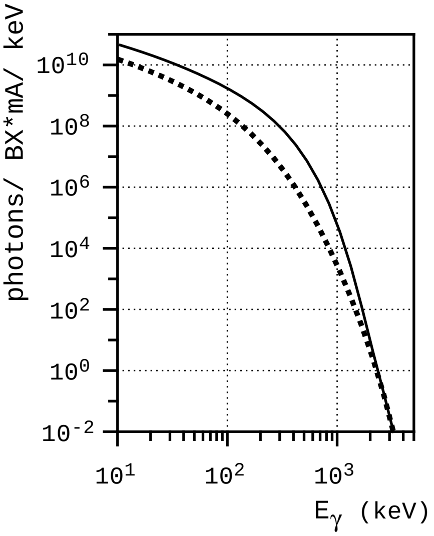


Figure 6: Photon energy spectrum in IP6. Nominal (100%) bump amplitude (full line), no bump (broken line).

5.1 Synchrotron Radiation

Symmetric vertical separation bumps are generated by electrostatic separators in the experimental insertions. These bumps span nearly 100 m through quadrupoles QS3 to QS6 on either side of the IP. The separated beams pass through the quadrupoles in the bump region off-axis and radiate therefore more and harder synchrotron radiation photons. SR-photon rates in IP6, with and without separation bumps, are tabulated in Fig. 5, the corresponding energy spectra are shown in Fig. 6.

However, not only does the bump radiate four times as many photons, but the generated photon fans have also larger angles with respect to the beam axis and will therefore strike the vacuum system closer to the IP. This can lead to a rapid increase of the photon background in the detectors, if the photons reach nearby vertical collimator jaws, from where they can be back scattered with high efficiency into the detectors.

To study the additional photon background from separator bumps the Monte-Carlo code "PHOTON" [32] has been extended to include electrostatic separators. With this modification symmetric and antisymmetric vertical bumps can be generated around the IP's. The expected, and experimentally observed, very steep increase by more than two orders of magnitude of the photon background rate for bump amplitudes above a certain threshold value, could be reproduced and is shown in Fig. 7.

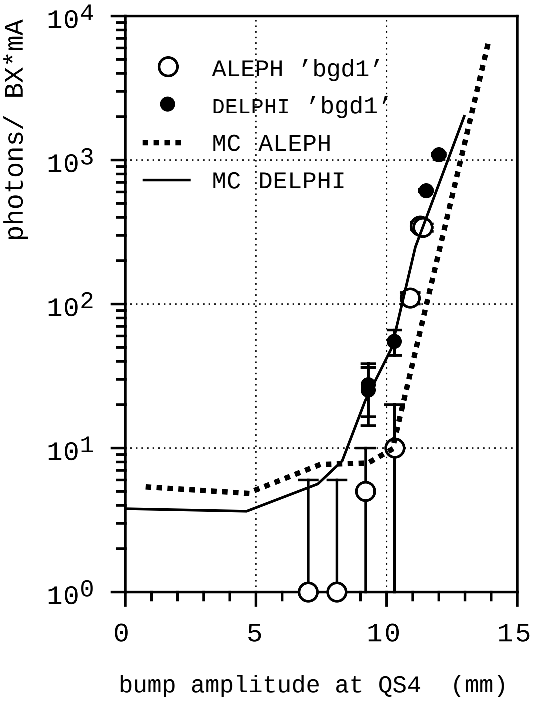


Figure 7: Comparison of simulated (lines) and measured (points) SR-photon rates in ALEPH and DELPHI as function of the separation bump amplitude.

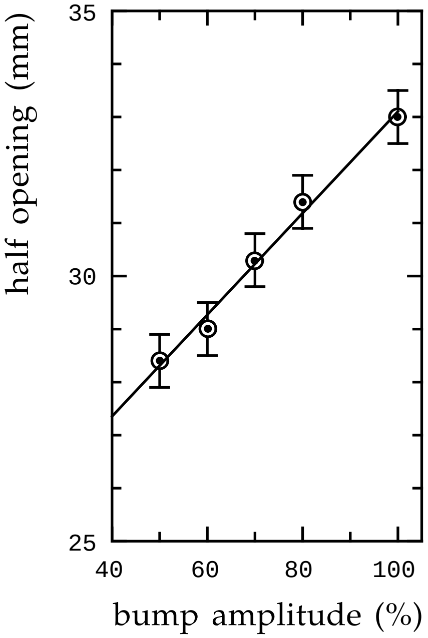


Figure 8: Smallest tolerable collimator COLV.QS1 opening in IP6 as function of the vertical separation bump amplitude in QS4.

The experimental points in Fig. 7 are normalised "figure-of-merit" photon background rates "bgd1" taken by ALEPH and DELPHI for various amplitudes of the separation bumps measured at QS4 [33]. Good agreement with simulations is obtained. The actual value of the threshold amplitude depends linearly on the opening of vertical collimators, in particular on the nearest collimator COLV.QS1 to the IP. The more this collimator is closed, the smaller is the amplitude at which photons radiated in the bump reach the collimator jaw and consequently produce unacceptably high photon background rates.

This dependence has been measured in OPAL and is shown in Fig. 8. As explained in section 5.2, collimator COLV.QS1 is required to protect the experiments from additional off-energy electron background, generated by the separation bumps, and must therefore be closed as much as possible.

The amount of SR-photon background from the separation bump depends also on the electron beam size and transverse density distribution. With bump amplitudes and collimator openings adjusted to safely stay below the photon threshold, large non-gaussian tails or sudden blowup of the vertical beam size can shift conditions into the high background region and lead to large spikes in the photon background. This phenomenon has been observed frequently during physics coasts with bunch trains in 1995.

The very high photon background rate from large beam displacements through the straight section quadrupoles can in principle be reduced by superimposing antisymmetric magnetic orbit bumps onto the electrostatic separator bumps. The separator bumps are symmetric in the sense that the electron and positron beams have the same displacement amplitude on both sides of the IP. A superimposed antisymmetric magnetic bump allows the reduction of the excursions of the incoming beams on both sides, while keeping the beam separation constant (Fig. 9). The increased radiation generated by the larger excursions of the outgoing beams will produce many more back scattered photons. However, the probability for these photons to reach the detectors is small due to the large distance between the point of impact and the IP, and because more than one scattering is needed to reach the detectors.

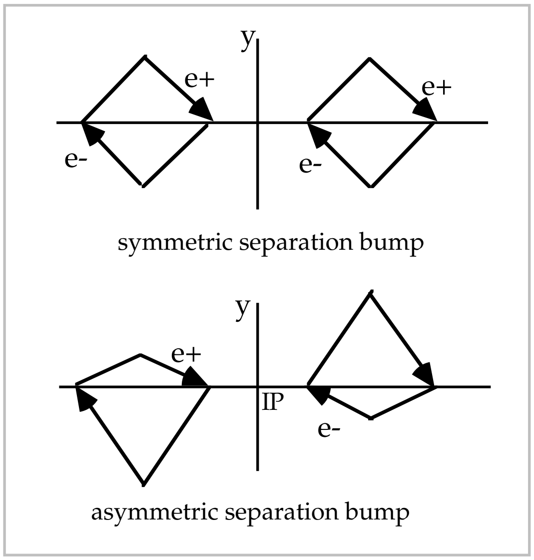


Figure 9: Schematic presentation of symmetric and antisymmetric vertical separation bumps.

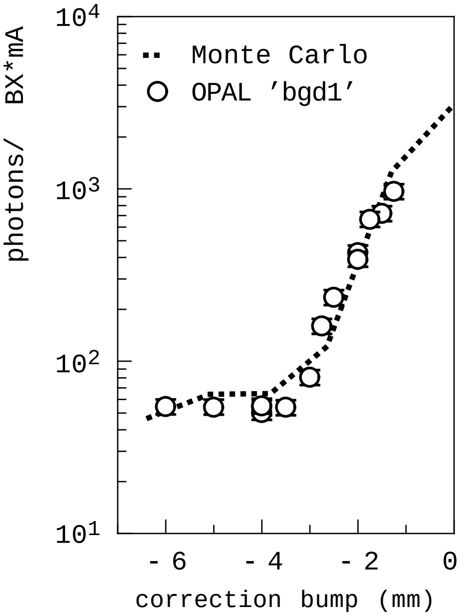


Figure 10: Comparison of measured and simulated photon rates in OPAL as function of the amplitude of a antisymmetric correction bump.

The effect of antisymmetric (correction) bumps has been simulated and compared to measurements [34] (Fig. 10). Starting with a bump amplitude of 12.6 mm for the incoming positron beam (100% bump in IP6), which is well above the threshold amplitude, the photon rate could be lowered by more than one order of magnitude, down to acceptable levels, by superimposing an antisymmetric correction bump of 3 to 4 mm. Again, simulations allow close prediction of the experimental results.

The superimposed antisymmetric magnetic bumps, however, produce unwanted vertical dispersion and were therefore avoided during 1995 physics data taking as much as possible. Instead, the beam separation around the IP's was chosen to stay well below the critical threshold bump amplitude of about 9 to 10 mm.

Synchrotron radiation masks, which were present in IP6 and IP8 during 1995, are designed to protect the experiments against photons with shallow incident angles of less than 3 mrad [35]. They do not intercept photons back scattered from the nearby collimators, and therefore provide no protection against photon background from the separation bumps. They will, however, not lead to increased photon background as long as their inner tips can be shielded against direct impacts of SR photons from the QS3 to QS4 region. This shielding is provided by the nearest vertical collimators COLV.QS1.

5.2 Off-Energy Beam Particles

During the 1995 energy scan, where a very accurate luminosity measurement was essential, it became evident that a bunch train specific component of off-energy background was present at the LEP luminosity detectors. This background family, clearly detected by OPAL [36], had very distinct features: a sharp peak in its energy distribution around 30 GeV and a concentration in the vertical plane at small radii. These characteristics made it particularly difficult to discriminate off-energy particles from Bhabha events and therefore endangered the envisaged precision of less than 10^{-3} for the absolute luminosity measurement.

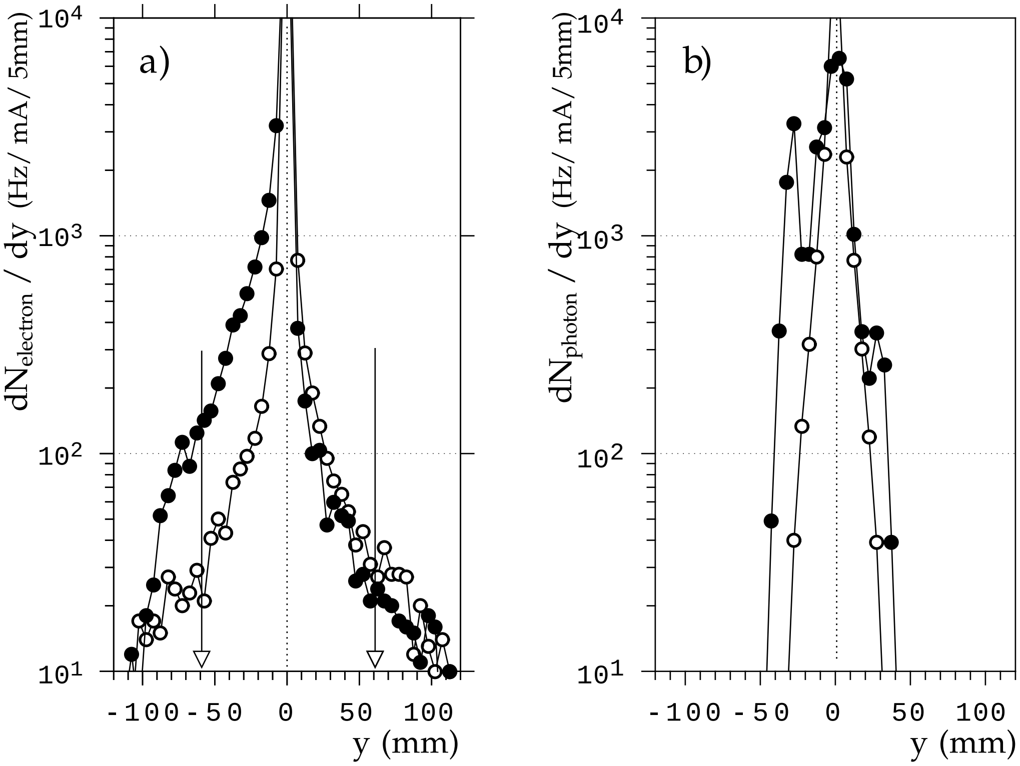


Figure 11: Simulated vertical density distribution of off-energy electrons (left) and bremsstrahlung photons (right) at 2.4 m from IP6, without (open circles) and with 100% vertical separation bump (full circles).

In order to understand the origin of this background, Monte-Carlo simulations of off-energy particles in LEP have been performed, using a special DECAY-TURTLE code [37]. The program was modified to include the effect of electrostatic separators on beam and secondary particles. Only bremsstrahlung by beam particles on rest-gas molecules has been included as source for off-energy particles. The contribution to background events from scattering with thermal photons has been shown to be negligible at LEP1 beam energies [38].

The simulations [31] showed that the effect was due to beam particles that have lost energy in a beam-gas bremsstrahlung interaction in the straight section upstream of the experiment and are then directed by the vertical separation bump into the upper and lower sectors of the luminosity detector. All the observed special features of this background family were confirmed by simulation. The vertical blowup of the off-energy electron beam at the OPAL luminosity detectors, 2.4 m downstream from IP6, due to the separation bump, is clearly seen in Fig. 11a. The vertical size of the bremsstrahlung photon beam is also enlarged, but stays within the vacuum chamber diameter of 106 mm (Fig. 11b). The pronounced changes of the radial and energy distributions of the off-energy background with $R \geq$ 60 mm at the luminosity detector are shown in Figs. 12a and 12b, respectively. As a consequence of the separation bump, off-energy particles are more concentrated at smaller radii and are focused into two energy bands, around 30 GeV into the lower detector, and a weaker component around 15 GeV into the upper detector. The origin of particles in the high momentum band are the RF regions around IP6, upstream of the downwards pointing first part of the separation bump for the incoming beam. The 15 GeV band originates from a region, much closer to the IP, along the upwards pointing part of the bump.

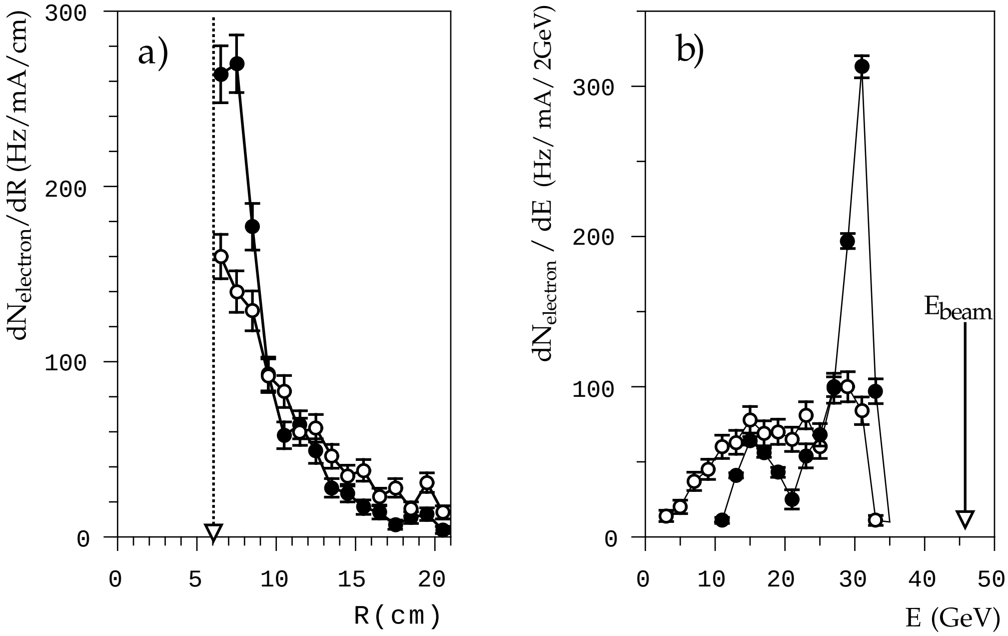


Figure 12: Simulated radial (left) and energy (right) distributions for off- energy electrons at 2.4 m from IP6, without (open circles) and with 100% vertical separation bump (full circles).

The good understanding of this particular bremsstrahlung background, obtained by detailed simulations, allowed the development of measures to protect against it. As verified by measurements [36], shown in Fig. 13, the vertical collimators COLV.QS1, located 8.7 m from the IP, are very efficient at stopping off-energy particles from reaching the interaction region in the presence of vertical separation bumps. Corresponding simulation results are shown in Fig. 14. The most disturbing high momentum component (full circles in Fig. 14) can be almost completely suppressed, if this collimator is closed to ±30 mm. As is clear from Fig. 8, this opening can only be reached, without generating unacceptably high photon background rates, if the vertical separation bump amplitude (in OPAL) is reduced to $\leq$70% of its maximum value. In addition, to ensure that collimator COLV.QS1 does not scrape into the beam tails, the vertical aperture limit must be closed from 30 σ_y to 26 σ_y [31]. During the second part of the 1995 energy scan, this solution was adopted, and gave the expected improvement.

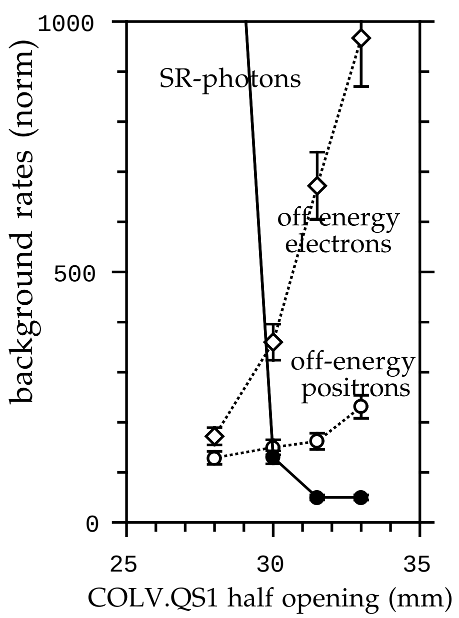


Figure 13: Measured background rates in OPAL as function of the collimator COLV.QS1 setting with 75% separation bump.

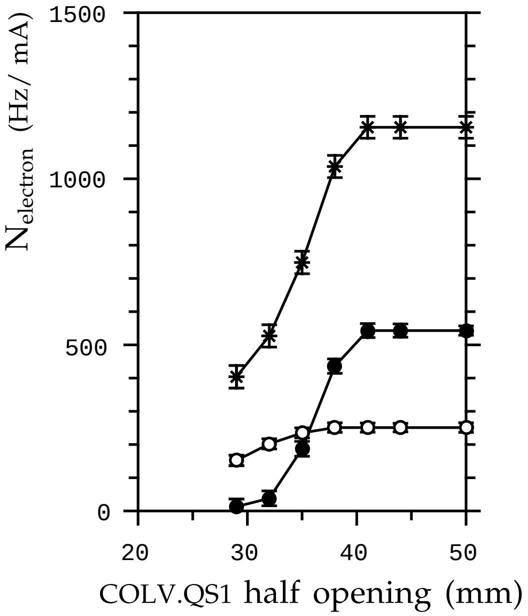


Figure 14: Simulated off-energy background at 2.4 m from IP6 vs. collimator COLV.QS1 opening. All background with R>60 mm (stars), within ±300 around Φ=90deg (open circles) and around Φ=270deg (full circles).

6 Beam Instrumentation

All modifications and development to cope with bunch trains [39] have been successfully implemented in the course of 1995. A review of the performance achieved by the various instruments during machine operation with bunch trains is presented and plans for further development are given.

6.1 Bunch Current Transformers (BCT)

In 1995 the original BCT acquisition system using long integration gates has been replaced by a 500 MHz digital sampling oscilloscope to measure individual bunches in trains [40]. Since all bunches were being measured on the same channel, excellent bunch to bunch normalisation was obtained. However, even after averaging, the 8-bit digitisation limited the relative precision of the single bunch measurements to about $500{\cdot}10^{-6}$, which was insufficient for monitoring single bunch lifetimes in real time. This must be compared to relative precision values around $90{\cdot}10^{-6}$ produced by the original multi-channel 16-bit acquisition system, prior to the introduction of bunch trains. As a result it was necessary to maintain both systems operational, the oscilloscope-based system providing single bunch currents and the original system providing fast monitoring of beam lifetimes and injection losses.

At the end of the 1995 LEP run, a test was made with another 16-bit acquisition system, known as BOSC, that has been successfully used in the SPS for a number of years. This system uses a peak hold detector and so is insensitive to timing jitter and can be gated to acquire individual bunches in trains. In a short experiment with beam, a relative precision of $25{\cdot}10^{-6}$ was obtained, which represents a considerable improvement both on the oscilloscope-based system and the original 16-bit acquisition system. It therefore seem likely that this system should be able to do the job of both these systems. A full evaluation will be made early in the 1996 LEP run, with a view to replacing the existing systems for the 1997 LEP run. It is, however, intended to retain one of the oscilloscope-based systems and reprogram it to scan for the distribution of beam around a complete LEP turn. In this way it will be possible to detect any unwanted parasitic bunches that have been injected outside the nominal positions or indeed any error in the relative timing of the two accumulated beams.

6.2 Bunch Current Equalizer (BCE)

A new Bunch Current Equaliser system has been implemented for the start of the 1995 LEP run to allow the filling of any combination of one to four bunches in each of four equidistant trains in each beam [41, 42]. The system is able to fill also a pretzel type beam of eight equidistant bunches. A dedicated VME system running LynxOS samples the individual bunch currents measured by the BCT each SPS supercycle and, taking into account the LEP operator's requirements, controls the LEP filling process via the injection kickers and the RF injection timing system. This system has proved to be very flexible in filling complex arrangements of bunches in 1995 and will also handle the simpler eight bunch beams (bunch train or Pretzel) planned to be used from 1996 on.

6.3 BOM Wide-Band (WB)

The external triggering proposed to allow position measurements for all individual bunches has been implemented and was used for data taking in 1995. This new mode of acquisition was very successful but suffered from instabilities of the TDM system used to transmit the necessary timing reference pulses. With optical fibre transmission replacing the TDM in spring 1996 this inconvenience should completely disappear. During 1995 physics data taking a new programme was scheduled to measure and log all bunch positions. These data have been analysed by the four LEP experiments in order to understand if, together with an accurate survey of the QS0 quadrupole vertical positions, they could provide an on-line assessment of the vertex position. The conclusion is positive [43] and these BOM data will therefore be included in all physics data taking for LEP2.

Vertical bunch positions measured on both sides of the experimental IPs have also allowed a precise observation of the orbit distortion due to beam-beam effect [44]. In the future, an automatic procedure will be set-up to perform a scan of the beam separation in no more than three minutes and adjust the bump parameters for head-on collisions.

Since the WB signal detection needs a clean interval of ± 40 ns, a BPM cannot work in the vicinity of a bunch crossing (± 6 m). In the future, when 32 more BPMs will be equipped with WB electronics in the even straight sections (see section 6.4), the number of those put out of service, as a function of the bunch separation, is shown in Fig. 15. With the bunch spacing of 118 lRF as chosen at the Chamonix Workshop 1996, all those BPMs will be available in bunch train operation.

6.4 BOM Narrow-Band (NB)

With bunch trains a number of BPMs located from Q5 to Q9 can measure only the beam incoming toward the IP and therefore do not deliver complete information on the closed orbit [45]. In order to improve this situation [46] it has been decided to convert four BPMs on each side of even IPs from NB to WB electronics. This conversion will be available in 1997.

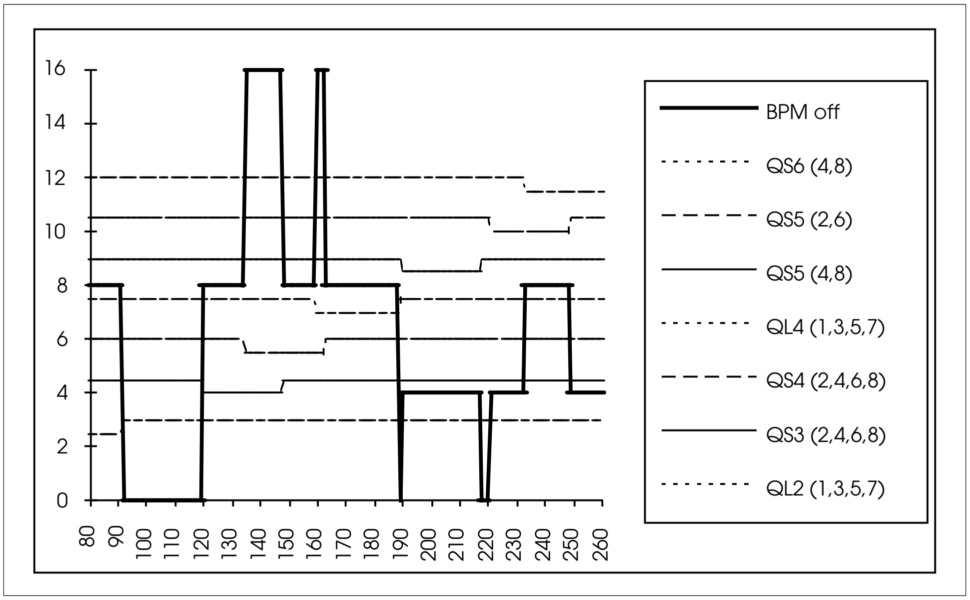


Figure 15: Number of BPMs put out of service as function of bunch separation (measured in RF wavelengths) for trains of 2 bunches

6.5 Q-meters

Two Q-meters of the new generation are now available with almost complete functionality: measurement in swept frequency mode, PLL mode and random excitation mode. PLL mode can be used for continuous tune measurements, random excitation can give a continuous display in the frequency domain. All modes of measurement are provided with a logging facility, some with an automatic logging. Selective excitation of several bunches cannot be done with bunch trains because of the length of the shaker pulses; but beam-beam modes can be measured when signals from two bunches are mixed with the appropriate phase [47]. This facility will be developed in the course of 1996.

6.6 Synchrotron Radiation Telescopes (BEUV)

In the normal mode of TV observation (20 ms integration) the measured beam sizes are based on a superposition of all bunch images, including beam oscillations and systematic closed orbit differences. This latter effect exists with bunch trains and can lead to some blow-up of the measured emittances. To be able to distiguish bunches in trains, studies were made on the fast intensifier-shutter and the related signal processing in the CCD detector. A second generation MCP (Multi Channel Plate) intensifier was installed in all telescopes to be able to acquire separately the various bunches of a train, which was used extensively to perform machine studies on the individual behaviour of the bunches. The fast acquisition of turn-by-turn beam images was improved. A scheme where the CCD detector is used as a memory and a signal processing component for turn-by-turn projection calculations is being developed [48].

To cope with the smaller vertical emittances encountered during 1995, many improvements and beam measurements have been made, with the result to be able to measure reliably vertical emittances down to 0.2 nm, a factor five smaller than originally foreseen. Much smaller beam size or emittance changes can of course be detected, which is useful for machine tuning [49].

The absolute calibration of the instrument is checked typically once a year in an MD devoted to cross-calibration of several instruments. But BEUV telescopes are measuring only beam sizes. In order to convert those values into beam emittances an exact knowledge of the actual betas and dispersions is needed. These lattice parameters are characteristic of the machine optics and of the actual running conditions and therefore should be obtained from a BOM harmonic analysis (1000-turn measurement) followed by a correction to take account of the beam-beam effects.

6.7 X-Ray Monitors (BEXE)

BEXE detectors allow turn by turn observation of vertical bunch sizes. Since the introduction of bunch trains, pulsing of the detector bias voltage has been implemented, tested with beam and found adequate to select any bunch in a beam. An on-line display which will provide the operation team with a continuous look at beam-beam instabilities is also being developed. In order to keep the same level of synchrotron radiation dose to the detectors as they had at LEP1, the BEXE enclosures will be rebuilt and displaced from QL12 to QL8 during the summer 1996.

6.8 Streak Camera

The requirement for the streak camera to measure different "family" bunches in trains (i.e. non-equidistant bunches) led to the development of a general fast timing module that permits the selection of a series of any bunches with a resolution of 12 ps and a jitter below 4 ps. It is used to measure up to 4 bunches per LEP turn, with at most one from each of the 4 equidistant trains.

A new installation of two additional dipoles has made it possible to modify the mini-wigglers in such a way that the parasitic light produced by quadrupoles QL4 does not interfere with the wanted light from the mini-wigglers [50].

6.9 Luminosity Detectors

The acquisition system of the eight pairs of Bhabha detectors has been adapted to allow parallel data taking for trains with up to four bunches and has been intensively used for luminosity scans during 1995. With the advent of LEP2, the Bhabha rate will decrease and the particle background increase in a disastrous way for luminosity measurement [51]. In order to reduce by an order of magnitude the number of accidental coincidences some new collinearity cuts will have to be introduced by measuring the position of both particles. To do so silicon strip detectors (both horizontal and vertical) will be added in each minicalorimeter and the data acquisition will be updated in consequence. Whenever an event is detected in a first level trigger, a full analysis will have to be done as fast as possible in order to minimize the dead time of the detector; this will probably require new DSPs. One pair of minicalorimeters of this new generation will be tested during 1996 and a conversion of the ensemble will be ready for 1997.

6.10 Polarimeters

The main difficulties encountered during polarimeter runs in 1995 were due to synchrotron radiation produced by the vertical separation bump at IP1. The mirror with a multi-layer dielectric coating which deflects the laser beam to meet the electron beam has been damaged by synchrotron radiation during 1995 and will be replaced by a more stable all-metallic mirror [52]. The problem encountered with outgassing of the supporting structure should be resolved by suppressing its chromium oxide coating [52]. But this mirror system will remain vulnerable to the radiation swept in the vertical plane.

7 Electrostatic Separators

A total of 40 electrostatic separators are required to achieve the closed orbit separation bumps in all LEP pits for the bunch train scheme [1].

Running with bunch trains in 1995 meant that the separators had to be operated in a new way, notably the necessity for high fields in all units throughout the physics data-taking. The effects of the 'new' separator system, are discussed with respect to the hardware performance, in terms of separator sparks, reliability and flexibility. The performance during the 1995 high energy run is briefly examined.

7.1 Hardware Summary

The separator hardware layout for bunch trains is documented at length in references [53, 54, 55]. The streamlining of the controls of the separator system is detailed in [56].

The conversion of the separation system to allow operation with bunch trains involved the addition of eight new vertical (ZL) separators near to QS7 in the even pits (designated ZL7). Each even pit has, therefore, a total of six separators, powered in three pairs (ZL2, ZL4 and ZL7). In the odd pits, eight existing ZL were displaced to positions near QL8 (designated ZL8). The four separators per odd pit are powered in two pairs (ZL1, ZL8). In all, a total of 40 vertical separators are needed for bunch trains. The use of the horizontal ZX and ZXT separators has been discontinued, as the high voltage generators and cables were needed for the ZL7 separators. The overall control structure was streamlined to use, in general, one high level application program, one operating system in the PCAs and one type of electronics in the equipment ECAs.

At the beginning of 1995, the plan was to remove the ZX and ZXT separators during the course of the year, after bunch trains had been proven. These separators were then to be transformed into vertical ZY units, and reinstalled in the 1995/96 shutdown at positions near QS2, in order to increase the separation available for LEP2. The actual performance of the machine with bunch trains during 1995 prompted a re-evaluation, and at present only the two ZXT separators have been removed and transformed into ZY. The eight ZX separators are still in LEP. The possible uses are as vertical ZY, as horizontal ZH to provide a horizontal vernier, or as ZX if pretzel is resurrected. All of these options will require resources and time to implement.

7.2 Mode of Operation

As a result of the operating constraints inherent to bunch trains, several changes were imposed on the way in which the separators were operated. The synchronous discharge switch could no longer be used to collide the beams, because the required separator voltages are non-zero. As a result, the method for bringing the beams into collision with a squeezed optics was to ramp the separator voltage slowly from the separated value to the colliding value, using an exponential interpolation to minimise the time required. This procedure typically took four or five minutes, compared to a few seconds with the old synchro switch method.

Another disadvantage was that the dedicated vertical vernier system could not be used to optimise the collisions; instead a method was developed using the main high voltage generators driven by a separate application program in the SloppySoft controls system. The discontinuation of the ZX and ZXT separators also meant that no horizontal vernier adjustment was possible.

Finally, the basic requirement to separate the bunches in the trains at all times meant that all 40 separators were operated at high voltage during physics conditions, which increased the probability of a spark occurring during physics conditions.

7.3 Separator Sparking

A detailed analysis of the separator sparking in 1995 is reported in [57]. The main conclusions are given below.

7.3.1 ZL4.R4 SPARKING WITH BUNCH TRAINS

During the final tests in the 1994/1995 shutdown, the separator ZL4.R4 in pit 4 exhibited a rather poor performance with positive polarity, which was on the limit for acceptance. Due to time constraints and the workload already imposed by the bunch train programme, the decision was made to leave the separator in the machine for 1995, but to change it if necessary during the first technical stop. At the start of the year, six sparks occurred in this separator, at which point the ratio of positive to negative voltage was altered to reduce the voltage on the suspect electrode. This manipulation worked, and the separator was operated in this way for the remainder of the year. It has now been removed from the machine and replaced with another unit.

7.3.2 ZL8 SPARKING IN PIT 3 WITH BUNCH TRAINS

At the start of the bunch train tests in 1994, and during the initial commissioning period in 1995, a problem emerged with repeated sparking on the ZL8 separators in pit 3 [58]. A total of 21 of the 61 sparks observed during 1995 were on these two separators (and 12 of the 21 sparks seen during the bunch train test period at the end of 1994). The sparking had the following features:

- All sparks occurred at 45 GeV;
- All sparks were on the ZL8 units, never ZL1;
- All sparks were in pit 3, never in pit 7;
- Sparks could happen with a single beam of either e^+ or e^-;
- Sparks were often associated with beam loss.

The search for the cause of this sparking led to the discovery of an aperture restriction in pit 3 caused by a misaligned vacuum chamber; however, removal of the pit 3 aperture limitation did not stop the sparking. Studies with scintillators to try and locate the cause of the sparking proved inconclusive. Finally, it was found that the sparking could be suppressed by operating the separators with positive high voltage only: the threshold negative voltage for sparking was between 10 kV and 30 kV. The separators were operated for the remainder of the year at a total positive voltage of 166 kV, instead of the nominal 114 kV each of positive and negative voltage; in addition the inter-electrode gap was reduced from 100 mm to 78 mm, to give 93% of the nominal field.

7.3.3 ZL4 SPARKING IN PITS 2 AND 6 WITH BUNCH TRAINS

From June 1995 onwards a series of sparks were observed in the ZL4 separators to the left and right of IP2 and IP6. A total of 16 sparks were recorded, and these sparks were generally associated with partial or complete beam loss. Almost all sparks occurred during the ‘adjust’ machine mode. The investigation of possible causes proved inconclusive, however nearly all sparks seemed to occur at moments when the separator voltage was being changed. The situation was substantially improved by reducing the amplitude of the bunch train bumps in these pits to 70% of the nominal value; subsequently only four sparks were seen on these separators over the final seven weeks of LEP operation in 1995.

7.4 System Constraints

The constraints with the bunch train separator system are that no horizontal vernier adjustment is possible; the main generators have to be used for the vertical vernier; the beams have to be brought into collision slowly; separator sparking in pit 3 effectively limits the bump amplitude to 93% of the nominal value.

7.5 Equipment Faults

The number of equipment faults in 1995 [57] was much lower than in 1994, due to the improvements in the control system, the reduction in the quantity and complexity of the operational equipment, and the simplification of the mode of operation, particularly in the vertical vernier adjustment.

7.6 Results from the 1995 High Energy Run

7.6.1 Separator sparking

At 65 to 68 GeV the Synchrotron Radiation (SR) from the LEP arcs has a critical energy of around 230 keV, as compared to some 70 keV at a beam energy of 45 GeV. Despite this, only one spark occurred during the 1995 high energy run, and this did not cause any beam-loss. During this period, the separators in the even pits were generally operated at 20% of the nominal fields; however, all separators in the odd IP were powered normally.

7.6.2 Radiation dose measurements

The measurement of the accumulated radiation dose on the separators during the 1995 high energy run is described in detail in [57]. Doses in excess of 10^7 rad were measured on the ZL8 separators in pit 3 and pit 7, and doses in excess of 10^6 rad on three of the ZL4 separators in pit 2 and pit 6.

The origin of the radiation is not known, with possible sources being SR from the bunch train bumps, SR from the polarisation wigglers (in pit 3 and pit 7) or particle losses on collimators (in pit 2 and pit 6). The correlation with the systematic sparking problems seen in pits 3, 2 and 6 earlier in 1995 (at 45 GeV) is also evident.

8 RF Equipment

8.1 Superconducting RF Units

The beam current and bunch structure for the bunch train scheme are quite different from the original LEP design specifications. The consequences of this on the higher order modes have already been discussed [1]. The geometry of the LEP superconducting cavity modules imposes that three different frequency regions have to be considered for a complete study of the HOM losses:

- Higher order modes below 1.1 GHz, the cut-off frequency of the cavity end flanges, stay within the cavities and have to be taken out by the HOM couplers. At both ends of a four-cavity module a conical transition to room temperature reduces the beam pipe diameter to 100 mm with a cut-off frequency of 2.2 GHz.

- Modes with frequencies between 1.2 and 2.2 GHz can leave the cavities but not the cones. They will partly be absorbed by the HOM couplers, if these couple to them, and partly be dissipated in the walls of the conical transitions.
- Above 2.2 GHz the modes can enter the beam tube. They will be absorbed by the beam pipe in the quadrupoles or in the inter-cavity equipment.

8.1.1 HOM COUPLERS

Four different types of HOM couplers were tested in LEP. The two CERCA bulk niobium modules are equipped with type 1 couplers, whereas the eight Nb/Cu modules are equipped with type 5 (5C, 5G, or 5M) couplers. These, contrary to type 1 couplers, have flatter high pass characteristics and are more likely to couple to the modes between 1.1 and 2.2 GHz.

The loss factors to be applied for type 1 and 5 HOM couplers were measured with one bunch in a single beam, in order to avoid any coherence between the bunches of the same beam and the two counter-rotating beams. These give loss factors of about 0.28 V/pC for HOM couplers type 1 and of about 0.44 V/pC for all three different HOM couplers type 5. A comparison with theoretical calculations of the loss factors [59] indicates that HOM couplers type 5 (C, G and M) couple to all modes below 2.2 GHz while type 1 couplers only extract about 60% of the power coming from these modes.

In the measurements of HOM power done so far with bunch trains there is no indication of full positive coherent addition of fields. However, we observe that for the bulk Nb cavities the extracted HOM power is higher than what would be obtained if just the powers were added. For the 32 Nb/Cu cavities the HOM power is about or even below the incoherent value.

8.1.2 HOM LOSSES IN THE CONICAL TRANSITIONS

Losses in the conical transitions were carefully studied in the Nb and Nb/Cu SC cavity modules. Power estimates were done by measuring the temperature profile variations of the conical transitions as a function of the beam current. Using the equation of heat and the geometry of the cones, the HOM power dissipated in the cones could be estimated to be about 2-3 W per module. However, the loss factors for frequencies above 1.2 GHz are strongly dependent on the bunch length [60]. Calculations including the whole system are presently being done [59, 61].

8.2 Longitudinal Feedback

Dipole coupled bunch oscillations are observed in LEP when the current per bunch exceeds about 150 μA and either four or eight equidistant bunches are circulating. These oscillations are damped with a feedback system operating at about 1 GHz [62]. The system has now been upgraded so that it can be used with eight bunch trains of upto four bunches each.

8.2.1 FEEDBACK FREQUENCY

The feedback system works at a frequency which is 247/87 times the RF frequency. For this reason the bunch spacing in a train was chosen to be either 87 or 174 RF wavelengths in 1995. For a different spacing the phase at the feedback frequency will be different for each bunch in a train. With only two bunches per train a bunch spacing which gives little phase error can be found. In 1996 it is planned that LEP will be operated with a bunch spacing of 118 RF wavelengths. The distance between bunch a and b in terms of wavelengths at the feedback frequency is then

$$\Delta_{a \to b} = \frac{247}{87} 118 = 335.0115 \lambda_{\mathrm{FB}}$$

and the phase error between bunch a and b is 4.1 degrees, which is fully acceptable. The same phase error with opposite sign is obtained with a bunch spacing of 143 RF wavelengths.

For more flexibility in the choice of bunch spacing the frequency of the feedback system could be changed to 17/6 f_{RF} = 997.93 MHz but when the bandwidth of the cavities was increased the minimum resonant frequency went up to 999.5 MHz. More work is required to bring the centre frequency back to its original value.

8.2.2 FEEDBACK VOLTAGE

In order to cope with bunch trains the bandwidth of the feedback cavities has been increased by a factor 7.7 to 2 MHz. This modification was done by changing the power coupler loop size and varying the field distribution in the seven cells with a new fixed tuner in cell no. four. Unfortunately this change has, as mentioned, increased the resonant frequency by about 2 MHz.

Although not initially foreseen, the voltage loss caused by this modification has been partially compensated by operating the system in pulsed mode (Fig. 16). During the passage of two counter-rotating bunch trains the power is about 250 kW and during the intervals about 50 kW. In this way the average power is kept below 100 kW and multipacting in the power coupler prevented. When the system was commissioned the feedback voltage was measured with an average power of 140 kW and found to be 0.79 MV. The calculated value is 0.83 MV. During routine operation in 1995 the power was about 100 kW and the voltage then 0.67 MV. The corresponding maximum damping time constant is about 7 ms.

8.3 Q_s Measurement System

The Q_s measurement system has also been upgraded for bunch trains. For the transmission to the PCR only two channels are available, one for electrons and one for positrons. The Q_s of any bunch in a train can be measured. The selection is done remotely. In addition, on request from the LEP experiments, the synchrotron frequencies of all the bunches of an electron and a positron train are measured simultaneously in the tunnel and recorded in the logging data base. Due to beam loading and the modulated RF waveform in the copper cavities Q_s is slightly different for the bunches of a train [1]. In most cases differences of only a fraction of a percent were measured, partly because the bunch current was rather low, partly because SC cavities were used.

8.4 Transverse Feedback System

Although not originally foreseen, the kicker amplifiers for the transverse feedback system have been completely redesigned for the bunch train scheme because tests have shown that it was not possible to generate four kicker pulses of a reasonable amplitude spaced by only 87 RF wavelength. In addition, it was found desirable to improve the linearity of the amplifiers for small amplitudes.

It was therefore decided that fixed amplitude kicker pulses would be used and that time for recovery between pulses would be given by using one of the two kickers for bunches a and c and the other for bunches b and d (Fig. 17). Due to the inductive load, the pulses are triangular if the amplifier is driven by square wave pulses. This characteristic is used for the modulation which is done by changing the timing of the kicker pulses as function of the required kick. The resolution is 0.7 ns. With a pulse

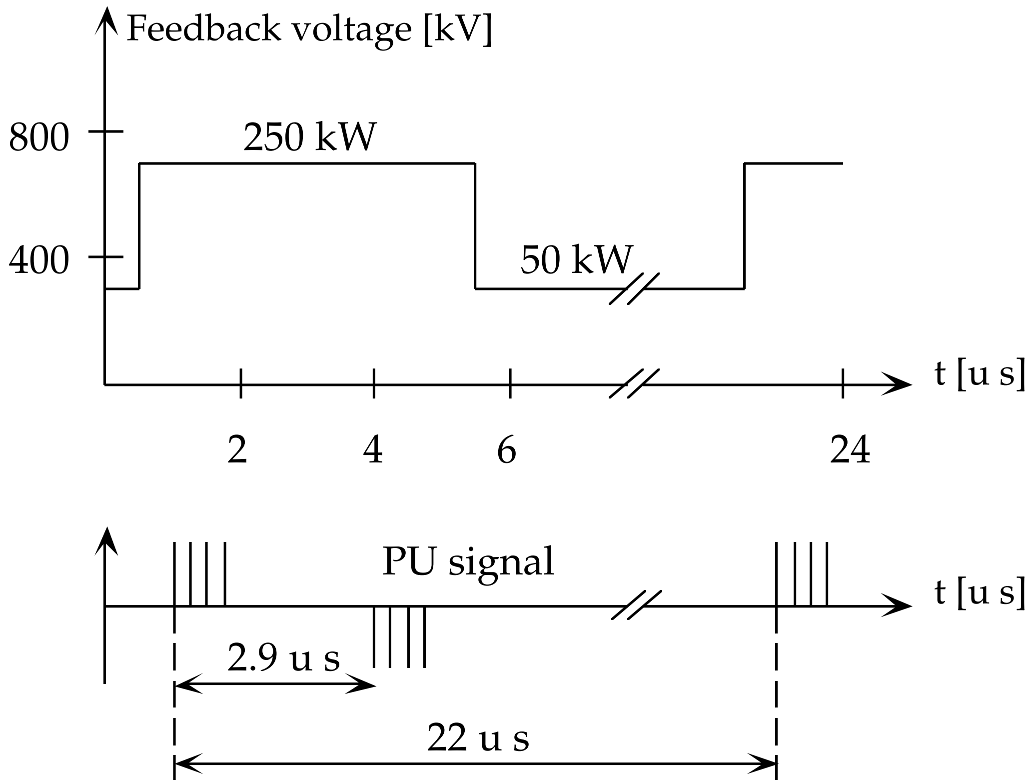


Figure 16: Timing diagram for operation of the longitudinal feedback system in pulsed mode.

amplitude of 10 A the maximum a.c. variation is ±5 A. This corresponds to a damping time constant of about 10 ms at 20 GeV. As seen in Fig. 17, both with and without modulation the bunches are given a d.c. kick which deflects them by 0.5 μrad at 20 GeV for a d.c. kicker current of 5 A.

The system was used in this mode during the 1995 runs. It made accumulation easier and prevented beam losses during the start of the ramp. In many runs the system was also used in physics. It was claimed that the transverse feedback system prevented background bursts in the experiments.

In 1996 LEP will be operated with two bunches per train spaced by 118 RF wavelengths. The system will be optimised for this mode of operation (Fig. 18). Due to the longer spacing between bunches a and b the same kicker can be used for both bunches. In addition, the delay between the two kicker pulses can be increased further by placing bunch a on the negative slope of the first pulse and bunch b on the positive slope of the second pulse if the modulation signal for the latter is inverted. A pulse amplitude of about 13 A can be reached which means that for the same energy the maximum damping rate will be a factor three higher in 1996 than in 1995.

9 Bunch Trains in 1996

In 1996 LEP will be operated at higher energies, i.e. above 80 GeV per beam, which implies new features that can have immediate consequences for the bunch train scheme:

- Smaller amplitudes of the separation bumps
- Two bunches per train
- Energy sawtooth and RF asymmetries

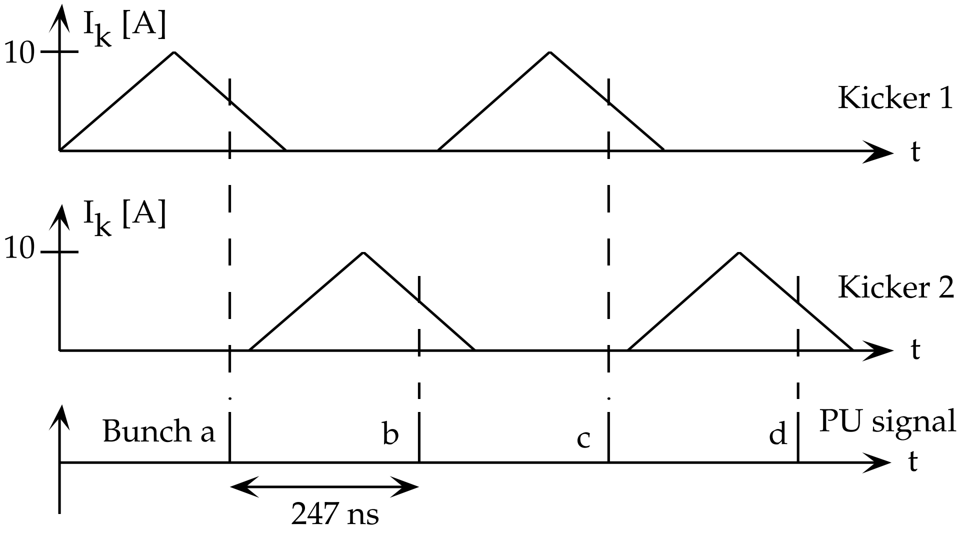


Figure 17: Timing diagram of the transverse kicker pulses for the 1995 runs.

Furthermore, the RF power available will limit the total current, and to obtain the highest luminosity it is advantageous to accumulate the highest possible intensity into a small number of bunches. It is therefore likely that in 1996 LEP will be first operated with four and later with eight bunches per beam.

9.1 Smaller Bump Amplitudes and Scaling of Side Effects

An immediate consequence of the higher energy is the reduction of the bunch train separation bumps if the layout of the separators or their strengths is unchanged: the bump amplitudes scale with the beam energy E as $1/E$. As a consequence the separation of the two beams at the parasitic collision points is also scaled by $1/E$.

Both reduced separation and bump amplitudes have consequences for all the side effects of the bunch train scheme. The most important are beam-beam effects, vertical dispersion and coupling. Although the coupling due to the solenoids is not a direct consequence of the bunch train bumps and is not affected by their reduction, it is of crucial importance for the performance and has a clear energy dependence.

9.1.1 BEAM-BEAM TUNE SHIFTS

For sufficiently well separated beams the tune shift from a parasitic encounter can be approximated by [63]:

$$\mid \xi_{\mathrm{x,y}} \mid \propto \frac{N\,\beta_{\mathrm{x,y}}}{y^2\,E} \quad \propto \quad N\,E$$

where N is the bunch population and y the vertical separation. Although E appears in the denominator of the beam-beam tune shift, its dependence on the separation is stronger ($\propto \; 1/y^2 \; \propto \; E^2$), and results in a tune shift which increases with energy. Further we hope for higher bunch intensities and must therefore expect a larger parasitic tune shift. It is believed, that the stronger damping at higher energies helps to allow for a higher tune shift but it should be minimized as much as possible. At LEP2 in 1996 we shall operate with two bunches per train and therefore can optimize the bunch spacing to reduce the overall beam-beam tune shift.

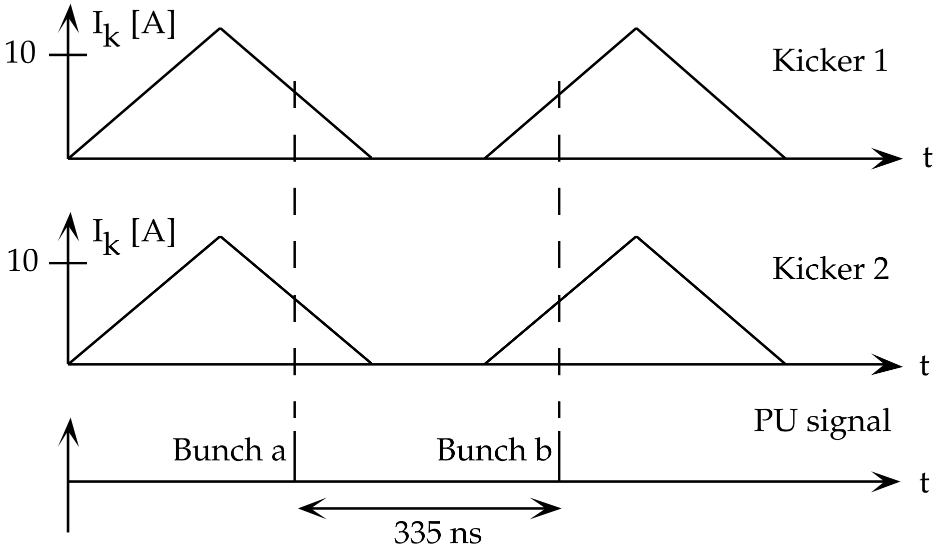


Figure 18: Timing diagram of the transverse kicker pulses for the 1996 runs.

9.1.2 BEAM-BEAM INDUCED ORBIT EFFECTS

Another important consequence of parasitic beam-beam interactions is their effect on the closed orbit. The coherent beam-beam kick changes the closed orbit of the bunches [63, 64] and furthermore, the closed orbit is usually different for the individual bunches of a train. This beam-beam kick scales approximately as:

$$\Delta y' \;\propto\; \frac{N}{y\,\cdot\,E} \;\;\propto\;\; N$$

Although the beam-beam kick increases proportionally to the decreasing bunch separation, the stiffer beam at the higher energy makes this effect practically energy independent. It is again possible to minimize this effect further by larger bunch spacing and fewer bunches. The case of two bunches per train is a special case where the two bunches of a train can be collided head-on at the interaction point by a proper adjustment of the separators at the collision points provided the bunch intensities are not too different. This is a consequence of the symmetry and the first bunch of a train has the opposite displacement to the last bunch of the corresponding train from the opposing beam [65, 8]. This clearly favours an operation of LEP with two bunches per train.

9.1.3 VERTICAL DISPERSION

The residual vertical dispersion is a direct consequence of the vertical bump and therefore all relevant parameters scale as the bump amplitudes, i.e. energy:

$$D_{\mathrm{y}}^{\mathrm{max}}, D_{\mathrm{y}}^{\mathrm{rms}}, D_{\mathrm{y}}^{*} \;\propto\; y \;\propto\; 1/E$$

All associated side effects such as e.g. energy offset at collision point, vertical emittance increase and excitation of resonances are therefore reduced.

9.1.4 COUPLING (SOLENOIDS)

In 1995 the vertical emittance was affected by not fully compensated coupling from the solenoid magnets of the experiments. Although not fully understood, it was found in operation and experiments [12] that the coupling compensation scheme strongly affected the luminosity performance in 1995 with bunch trains. Since the fields of the solenoids remain constant, their effect decreases with increasing energy $\propto 1/E$. Such behaviour has already been observed in the run at 65 GeV in October 1995 where the vertical beam emittance was significantly reduced compared to 45.6 GeV.

9.2 Bunch Spacing for fewer Bunches

For the maximum number of four bunches per train the choice of the bunch spacing was very limited and constraints from the longitudinal feedback system led to a spacing of 87 λ_{RF}. For less than four bunches per train the spacing can be chosen with more freedom, respecting however the boundary conditions from the longitudinal feedback system and the BOM (cf. Sections 6 and 8).

With two bunches in one train, it is possible to choose a spacing which minimizes the parasitic beam-beam effects. This is illustrated in Fig. 19, where the integrated parasitic beam-beam tune shift for each bunch in a train is plotted for the horizontal and vertical planes. For the ideal bunch spacing the tune shifts assume a minimum for **both** planes and **all** bunches of a train. For two bunches per train there is no difference between the two bunches due to the symmetry and they have the same tune shifts provided the bunch intensities are not too different. The assumptions for this calculation are:

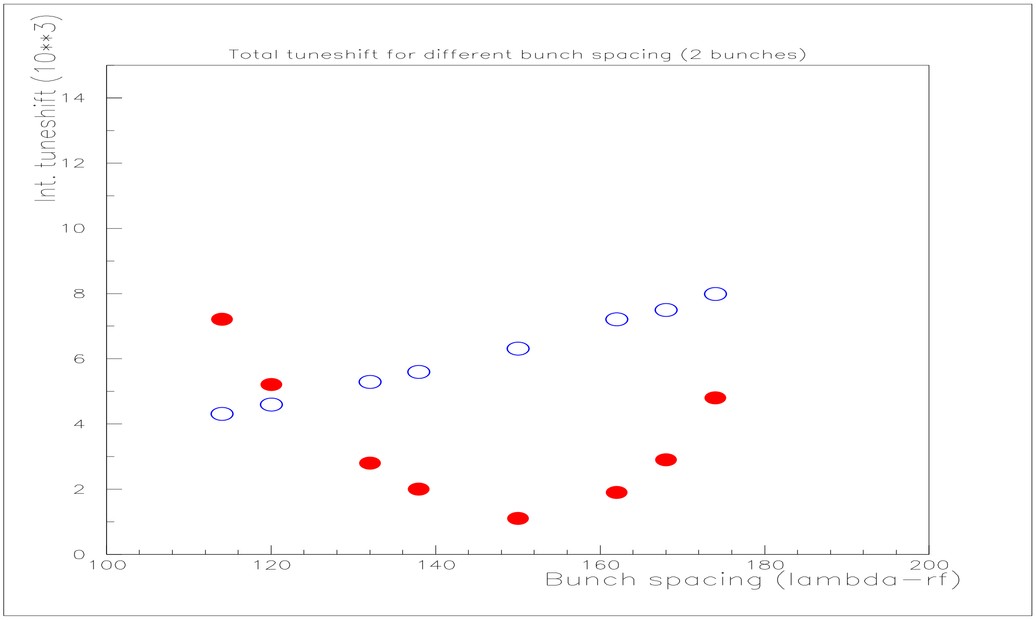


Figure 19: Integrated parasitic beam-beam tune shift as function of bunch spacing, 2 bunches per train. Open symbols for vertical and full symbols for horizontal plane.

- Optics with phase advance: $108^0/60^0$ and β_x^* = 1.25 m.
- Energy is 87 GeV
- Full bump is on
- Intensity per bunch 0.5 mA, all bunches equal
- Emittances: $\epsilon_x = 30$ nm, $\epsilon_y = 0.33$ nm (corresponds to $\xi_y = 0.045$ in collision)

From Fig. 19 one can determine that a spacing between 115 and 160 λ_{RF} would be a good choice with a minimum of the envelope of both curves around 124 λ_{RF}. The choice of the parameters for the calculation does not affect the results substantially because the results are either rather insensitive (e.g. optics) or they just scale with the parameters (energy, intensity etc.). Together with the constraints described above the recommended spacing for LEP in 1996 is 118 λ_{RF} [67]. Other side effects which depend on the separation are also reduced.

9.3 Effects of Energy Sawtooth and RF Unit Trips

An important difference to the operation of LEP at lower energies is the strongly increased synchrotron radiation and therefore the increased energy loss per turn. This results in a sawtooth orbit in the horizontal plane and an asymmetric energy distribution around the ring. It also implies a small horizontal separation of the electron and positron beams.

Furthermore, when the energy is not matched, the vertical separation bumps are not exactly closed and it is important to evaluate whether this non-closure is correctable with an appropriate separator adjustment. The non-closure of each bump depends on the local energy offset and the effects from the different bumps in the eight interactions points have to be added. The resulting non-closure therefore depends on the energy distribution around the whole machine. Unlike the orbit differences caused by parasitic beam-beam kicks, all bunches of a train are affected in the same way.

9.3.1 ENERGY SAWTOOTH AT 87 GEV

The scenario used for the calculations is the one foreseen for September 1996 where 87 GeV are achievable. The total RF voltage used in the structure was 2100 MV. The horizontal positron orbit for this distribution is shown in Fig. 20 for 87 GeV. It can be seen that the horizontal excursion can be as large as 2.5 mm. The asymmetry in the horizontal orbit is a consequence of the asymmetric distribution of the RF units.

9.3.2 EFFECT OF ENERGY SAWTOOTH AND RF UNIT TRIPS ON BUMP CLOSURE

This asymmetry is enhanced when some RF units have tripped and the RF distribution becomes even more unbalanced, resulting in a larger non-closure of the bumps.

To evaluate this non-closure the closed orbits in the presence of the bunch train bumps were calculated for 4 RF scenarios and the results are shown in Table 2. Without any RF, i.e. without a sawtooth, the bumps are obviously completely closed and for the nominal RF structure the non-closure is in the order of μm. In the horizontal plane the separation is several μm, depending on the interaction point. The asymmetric case where all RF units on the right of IP4 and IP8 are off is not stable and is a scenario with the largest energy offsets at the even interaction points and the biggest vertical separation. It was

Table 2: Vertical and horizontal separation in μm at interaction points for different RF configurations

	Vertical separation				Horizontal separation			
RF scenario:	IP2	IP4	IP6	IP8	IP2	IP4	IP6	IP8
No sawtooth	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
All RF o.k., 87 GeV	+1.1	+1.1	+1.2	+1.0	−1.2	−8.7	+0.7	+8.4
RF right of 4 and 8 off	−3.4	−4.4	−3.6	−4.5	+0.4	−10.0	+1.1	−10.0
RF around 8 all off	−2.2	−1.3	−0.3	−0.7	−3.6	−10.0	−3.1	−12.5

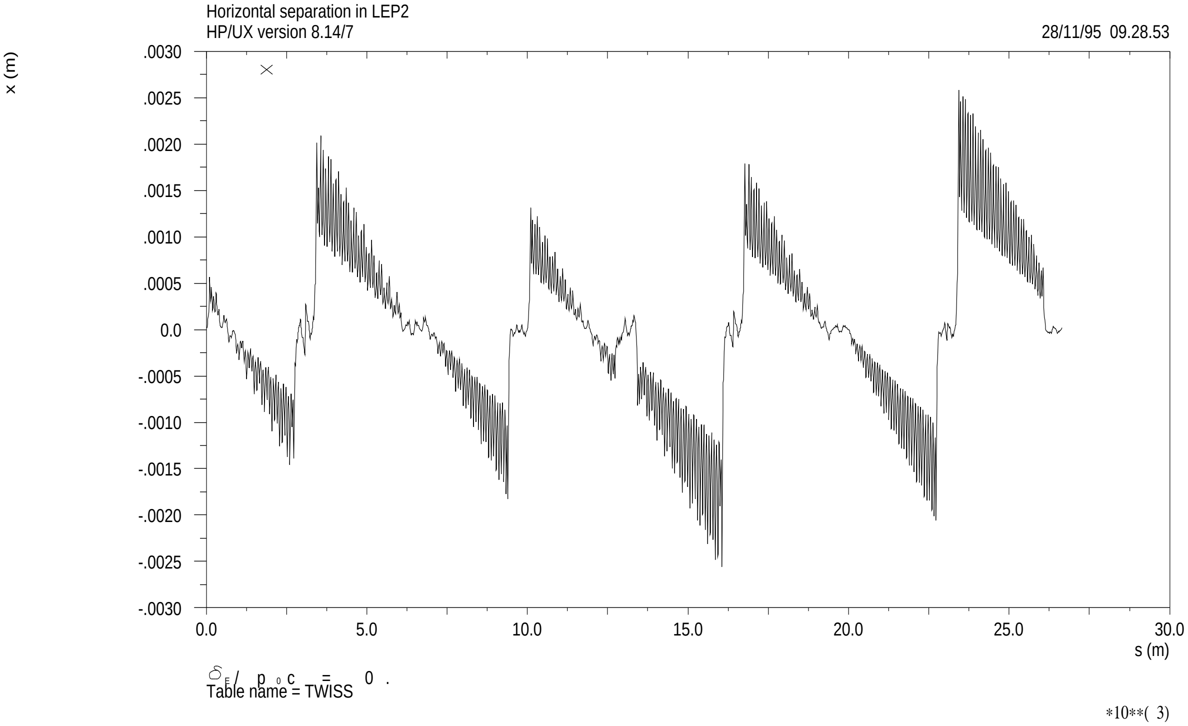


Figure 20: Horizontal positron orbit (sawtooth) at 87 GeV with all RF units on

studied to evaluate the magnitude of these effects in the worst case. For this case the non-closure can be as large as 4 to 5 μm in the vertical plane, still small enough to be easily corrected with the separators. The horizontal offset is enhanced and is up to 10 μm in the horizontal plane, still much smaller than the horizontal beam size. The fourth scenario where all RF units around one even interaction points are off results obviously in the largest energy offsets in the odd points since the RF voltage distribution becomes very localized. This is an important source for poorly closed bumps.

9.4 Are Bunch Trains Compatible with other Schemes?

An important question is the compatibility of the bunch train scheme with alternative schemes such as 4 equidistant bunches per beam which would be the preferred scenario when the total intensity is limited by the available RF power. Such a scheme was indeed used for most of the LEP operation at 65 and 68 GeV and its success indicates that there are very few problems. To completely restore the old situation (i.e. before pretzel or bunch trains) the separators next to the even points have to be re-conditioned (polarity change) and two separators in each of the odd pits have to be moved to their original positions. However, the successful running at 65 and 68 GeV and in particular the small vertical emittances achieved suggest that such a modification is not necessary. In particular since the effect of the bumps get smaller with increasing energy.

A possible alternative scenario for an operation with 4 bunches is a scheme with two trains of two bunches in each beam which has the advantage that the bumps in the odd points can be switched off.

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