OPERATION OF LEP WITH BUNCH TRAINS

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ABSTRACT

Following an intensive MD program in 1994, a bunch train scheme was adopted as the operational mode for LEP. The configuration was used throughout 1995 and produced record luminosities. The year culminated in a high energy bunch train run which produced encouraging results for LEP2.

In spite of this, the bunch train scheme met with varying degrees of success and the overall performance was not as good as expected. The performance of the machine is presented, together with the problems encountered and the various optimisation techniques used. The performance of related hardware and instrumentation is discussed.

1. INTRODUCTION

The bunch train scheme for LEP was partially developed in 1994 [1], and then commissioned operationally in 1995 [2]. The two prime motivating factors in developing the scheme were:

1. To increase the luminosity at Z_0 energies by increasing the number of bunches;
2. To raise the maximum bunch current in 8 bunches per beam for operation at W pair energies [3].

The 8 bunch Pretzel scheme [4] was limited at injection energy to bunch currents significantly less than the 1mA hoped for. For 45 GeV operation this limitation was not a significant problem, since the beam-beam effect limited the bunch current to around 350 μA, well below the maximum attainable at injection energy with pretzel.

The plan was to operate LEP in 1995 with four equidistant trains of bunches in each beam. Each train was about 220 m long and consisted of up to four bunches. The results from MD in 1994 had led to high expectations of possible deliverable luminosity. The results were not as good as expected.

2. CONFIGURATION

The bunch train scheme used electrostatic separators to provide extended local separation bumps around the interaction point (IP) such that: a) trains of up to four bunches, separated by 87 λ_{RF} could be accommodated; b) all bunches in the counter-rotating e+ and e- beams were separated at all encounters at injection energy and during the energy ramp; c) separation was provided for all parasitic encounters during physics; d) collisions could take place at the four experimental IPs e) a vertical 'vernier' bump could be superimposed at these points to allow fine adjustment of the collisions. The bunch train bump in an experimental IP is shown in figure 1.

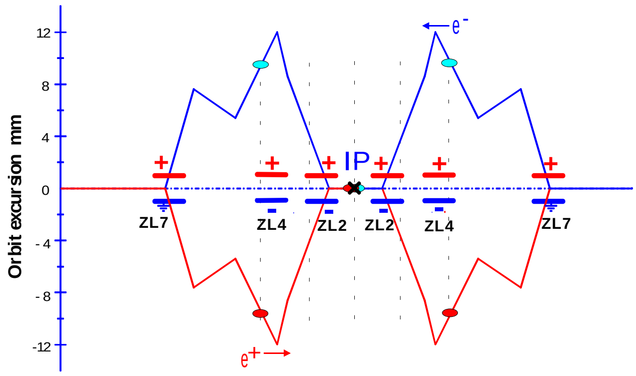

Figure 1 : The bunch train separation scheme for one experimental interaction point, with collisions at the IP.

3. OPERATION WITH BUNCH TRAINS IN 1995

3.1 Commissioning

During the commissioning of the bunch train scheme particular attention was given to the control of radiation to the experiments at injection, bunch train bump closure at 20 and 45 GeV and the background seen by the experiments.

The first physics runs with two bunches per train were performed with a total beam current of 3 mA. During this period problems with separator sparking caused many fills to be lost. Many studies were also undertaken to try and understand a significant non-closure of the bumps, both at injection and during physics. Injection efficiency was rather low and the radiation doses received by the experiments seemed to be sensitive to the bump amplitude in the non-experimental interaction regions. Later, an aperture restriction was found in one of these regions, caused by a mis-aligned vacuum chamber.

The logbook during this period reads like a litany of vernier optimisations, background spikes, poor lifetimes and coherent oscillations as operations struggled to master bunch train running. However by the end of this period the typical total currents were around 4.5 mA and the beam-beam tune shift (ξ_y) was above 0.03 [5].

Although the performance was improving, it was still not optimal with two bunches per train. It was clear that the push had to be towards trains of three and four bunches.

As proof of principle a small number of fills were performed with three bunches per train. These attempts were reasonably successful with around 6 mA total beam current, peak luminosities of 1.2 10^{31} $cm^{-2}s^{-1}$ and a ξ_y of around 0.02. Thus encouraged, trains of four bunches were attempted. During the last week of running before the technical stop, extra damping wigglers were commissioned and used to accumulate 9 mA. This could be ramped to physics energies, but many problems were encountered going into collision. Low lifetimes were observed, especially for the outermost electron bunches. Six physics fills were performed during this week: all but two had missing bunches. Typical physics conditions with the full compliment of 32 bunches saw currents of around 250 μA /bunch (~6mA total), peak luminosities of 1.5 10^{31} $cm^{-2}s^{-1}$ and a ξ_y of around 0.02.

In a little over a month and a half, operation with two bunches per train had been successfully proven many problems resolved. Principle among these were: sparking, mis-alignments, radiation at injection and vernier scanning. Operation with three bunches per train had been demonstrated, and the first dogged attempts with trains of four had been made.

3.2 Energy Scan

For the energy scan of LEP in 1995 it was decided to use three bunches per train, after several more failed attempts to use the full four bunch per train configuration. The bunch configuration and other parameters of the machine had to be fixed in order to provide a stable platform for the painstaking process of scanning.

Concentrating on a single configuration allowed a slow but steady improvement in the performance, and by the middle of the period over 8 mA were regularly being brought into collision. Typical initial luminosities were around 1.5 10^{31} $cm^{-2}s^{-1}$, corresponding to a ξ_y of about 0.03. The bunch train scheme was at least equalling the best performance of pretzel [6], and peak luminosities continued steadily to evolve, as shown in figure 2.

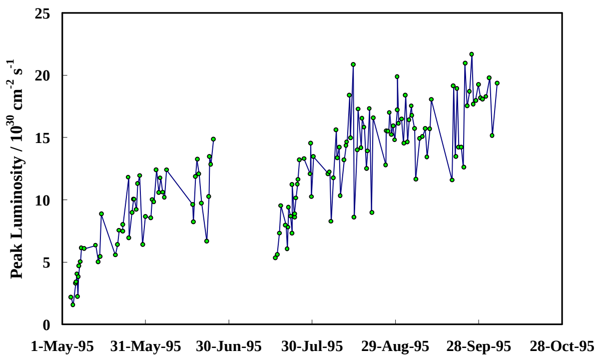

Figure 2 : Evolution of peak luminosity with bunch trains through the commissioning and energy scan periods.

The main bunch train related problem during this period was the continued experimental background storms, apparently related to beam instabilities. Towards the end of the period things had settled down so much that the principle question had become: "*why is the ξ_y so low?*" (Recall that ξ_y = 0.045 had been achieved with pretzel, and steady running above ξ_y = 0.04 was common.)

Steady running continued until the end of dedicated Z_o physics with special attention paid to regular vernier scans [7] and, by varying the RF frequency between scans, measurement of residual vertical dispersion at each experimental IP [8].

The bunch train scheme at this point was a qualified success. A lot of effort had gone into operating LEP in a completely new way, resulting in a reasonable performance. However, the effects of parasitic encounters [9,10] had lead to the abandonment of four bunches per train, and even with three bunches per train had resulted in lower beam-beam tune shifts than expected.

3.3 The High Energy Run

The final running period of LEP was planned at intermediate energies, between 65 and 70 GeV per beam. The commissioning of the machine for higher energies was very quick and within four days the first 65 GeV physics run took place. Because of a cautionary total beam current limit imposed by the RF group operation was with one bunch per train.

In the final physics fill of 1995 a current, of 5.6 mA was put into two bunches per train and collided at 68 GeV. This was a big success, producing peak luminosities of 3.4 10^{31} $cm^{-2}s^{-1}$. In another experiment using two bunches per train at 45 GeV, values of ξ_y in excess of 0.04 were recorded, due to the ability to collide both bunches head on in this configuration [11].

4. HARDWARE PERFORMANCE

4.1Electrostatic Separators

With bunch train all 40 separators are operated at high voltage during physics. This increased the probability of separator sparking and related beam loss, and systematic sparking was observed in several separators, cured either by operating with positive high voltage only, or by reducing the bunch train bump. The high energy run was an important test of the sensitivity of the separators to higher energy photons (ε_c = 230 keV at a beam energy of 68 GeV), with only one separator spark recorded despite high radiation doses of over 10^7 rad measured at some separator locations [12].

4.1 Radio Frequency

Bunch train operation allowed high currents to be accumulated which facilitated the debugging of the new superconducting RF systems. Higher order mode measurements showed that full coherent addition of cavity fields did not occur, although in some cases the higher order mode power exceeded that expected from addition of cavity powers. The longitudinal feedback system ran with a fixed bunch spacing of 87 or 174 λ_{RF} the optimum for four bunches per train. For 1996 this will be changed to 118 λ_{RF} to allow operation with two bunches per train. The modified transverse feedback system performed very well, making accumulation easier and preventing beam losses at the start of the ramp. The system was also used in physics to prevent background bursts in the LEP experiments.

4.3 Beam Instrumentation

The bunch current transformers used fast-sampling oscilloscopes to allow measurement of single bunch currents, and the new bunch current equaliser was indispensable for filling the machine. It was demonstrated that a rapid optimisation of luminosity could be made by scanning the beam separation whilst measuring the orbit distortion due to the beam-beam effect [13]; this will be implemented in 1996.

The synchrotron radiation telescopes were able to measure beam sizes of individual bunches in a train, although the absolute calibration of the instrument was only as good (or as bad) as the knowledge of the dispersion and beta functions at the instrument location. More realistic information should be available in 1996. The polarimeter worked well, although synchrotron radiation caused damage to a dielectric mirror and out-gassing from the support structure, and these components have been upgraded for 1996.

5. CONCLUSIONS

Initial tests in 1994 with two trains of four bunches colliding in two interaction points had raised expectations of the potential of bunch trains to almost hysterical levels. The reality, necessarily, fell short.

First, a totally new way of running the machine had to be mastered by the operators. New methods of optimisation had to be developed. These concerned not just luminosity, but backgrounds and radiation. At the end of the day, however, it was felt within operations that the bunch train scheme was in fact easier to control than pretzel. Secondly key equipment, such as separators, were pushed to new limits, forcing the understanding of their performance up a steep learning curve. Thirdly, theoretical and practical understanding of the many side effects that arise from colliding bunch trains, in particular the effects of the parasitic encounters, had to be mastered. This inevitably took some time.

However, a radically new way of running LEP was commissioned successfully. It was challenge to the equipment groups, beam instrumentation, operations, accelerator physicists and management, and as such stimulated frank open discussion, improvements and understanding. Not withstanding the lower than expected luminosity yield, the final results of the year bode extremely well for LEP2 [14].

6. ACKNOWLEDGMENTS

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