LEP Operation in 1993 with the Pretzel Scheme

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Abstract

LEP started up in 1993 with 4 positron and 4 electron bunches and reached rapidly the peak performance of 1992 with luminosities of about $1.1 \cdot 10^{31} cm^{-2} s^{-1}$. A new optics, with a betatron phase advance of 90° in horizontal and 60° in the vertical plane was used throughout 1993. This optics appeared at least as good as the 90°/90° optics of 1992 for luminosity with the additional advantage of a better control of the vertical orbit, important to allow transverse beam polarisation.

After the recommissioning phase with 4 on 4 bunches, LEP was routinely operated with 8 on 8 equally spaced bunches, avoiding midarc collisions by the pretzel scheme. Peak luminosities increased up to $1.8 \cdot 10^{31} cm^{-2} s^{-1}$ and the total integrated luminosity during 1993 reached 40 pb^{-1} compared to 28.6 pb^{-1} for the previous year. Half of the luminosity was delivered at the peak of the Z-resonance and one quarter each 2 GeV above and below the resonance. Twice per week, several hours at the end of physics fills were devoted to a precise determination of the beam energy using the technique of resonant depolarisation.

1 FILLING AND PREPARATION FOR PHYSICS

As in previous years, four bunches of positrons and electrons, supplied by the SPS, are injected at 20 GeV beam energy into LEP [1]. A time slot of 4.8s of the 14.4s SPS supercycle is used for this purpose. The RF synchronisation between the accelerators is controlled from LEP. To fill 8 bunches per beam, the programmable delay is set to automatically switch back and forward by the equivalent of 1/8 of a turn of LEP in each SPS supercycle. Accumulation of 8 bunches to say 0.3 mA in each bunch is therefore expected to take twice as long as the filling of four bunches to the same bunch intensity. Bunch intensity equalisation is achieved by automatically disabling the kicker timing for individual bunches, that reached the required threshold.

The total accumulated current per fill is shown in fig. 1 . Going from 4x4 to 8x8 bunches, the total accumulated intensities increased from about 3.6 mA (0.45 mA per bunch) to 5.6 mA (0.35 mA per bunch). The bunch current for single positron and electron beams is limited by the transverse mode coupling instability. For two beams with 4 bunches each, it was observed that the threshold for instabilities is lowered by residual beam-beam effects[2]. With 8 bunches per beam, there are extra long range beam-

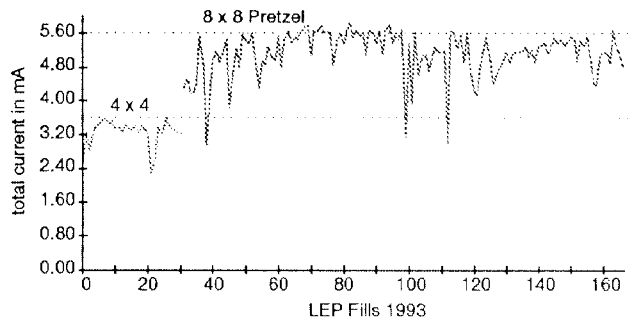

Figure 1: Total accumulated intensity at 20 GeV injection energy per fill in 1993

beam effects from the close midarc encounters resulting in a further reduction of the threshold for instabilities by typically 20 to 30 % [3].

The filling conditions for LEP were quite reproducible and currents of 0.30 mA per bunch could often be reached with no or only minor adjustments. The working point for injection was Qx=90.28, Qy=76.22 and Qs=0.08. Small, positive chromaticities, very similar currents in all bunches and a longitudinal feedback system using a dedicated cavity operating at a frequency of 1 GHz, were important to accumulate currents beyond 0.30 mA per bunch.

Damping, emittance and polarisation wigglers are installed in LEP. The damping wigglers are operated in a dispersion free region. They are fully excited at injection to reduce damping times and to lengthen the bunches from 0.3 to 1.2 cm. The bunchlength could be further increased to 1.5 or 2 cm using the emittance and polarisation wigglers. The emittance wigglers were used occasionally at injection but did not allow significantly higher currents. The polarisation wigglers made orbit control through the ramp more difficult and less reproducible and were not used in standard operation in 1993.

The preparation for physics proceeds through several steps. The beam is ramped from injection energy to 44.125 GeV in 6.5 minutes. The change of optics, reducing the vertical beta function at the interaction points from 21 cm to 5 cm for physics, is done at constant energy in the squeeze procedure and lasts 1 minute and 18 seconds. The final physics energy of 44.689, 45.572 or 46.482 GeV is than attained in less then one minute. Orbits and tunes can be checked after each of these steps and corrected if necessary.

The initial working point for physics is Qx=90.30, Qy=76.16 and Qs=0.065. Orbits are corrected and the

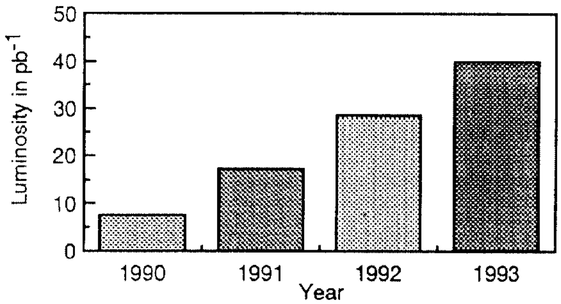

Figure 2: Integrated luminosity per year

emittance wiggler is turned on to maximum excitation before beams are brought into collision. The wigglers increase the emittance from 12 to 36 nm and avoid excessive beam-beam effects. For currents of 0.30 mA per beam and 36 nm emittance, the tune shifts can not exceed a value of 0.023. The physics coast is declared from the moment that collimators have been moved to tight physics settings. Background conditions for the experiments have always been good at LEP1. In 1993, background conditions further improved as consequence of the increased horizontal beta value at the interactions [4].

2 PERFORMANCE FOR PHYSICS

The increase in the luminosity produced by LEP per year can be seen in fig. 2. The performance of LEP operation over the last years is summarized in table 1. Due to general improvements and streamlining of procedures, the average filling time did not increase significantly by going to 8x8 bunch operation. The overall efficiency is calculated as ratio of time in coast over the total time scheduled in physics. It includes downtime due to faults and the time spent in preparing the physics coast like filling and ramping. The efficiency in 1993 increased to 55 %, or 61 % if the time spent for energy calibration is added to the coast time.

3 EXPERIENCE WITH THE 90°/60° OPTICS

The 90° phase advance in the horizontal plane was chosen for its low emittance of only 12 nm, allowing high luminosity down to low currents. The vertical beam-beam tune shift parameter ξ_y (proportional to the ratio luminosity / current), can be kept at a constant level of $\xi_y = 0.03$ down to 0.13 mA bunch current.

The vertical phase advance was decreased from previously 90° to 60° in 1993. This was mainly done to allow significant levels of transverse polarisation. With a fixed number of pickups, the orbit is better sampled for a lower phase advance and allows better correction. The LEP machine was also completely realigned in the winter shutdown between 1992 and 1993 [5]. High levels of polarisation were in fact achieved in 1993. Polarisation and energy calibration using resonant depolarisation are discussed in separate contributions to this conference [6]. A good control of the vertical orbit is also of primary importance to minimize dispersion and optimize luminosity.

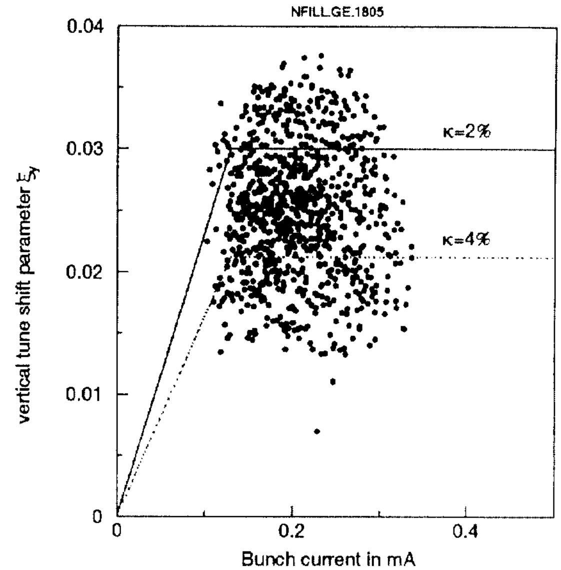

Figure 3: ξ_y dependence on current in Pretzel operation 1993. The expected behaviour for emittance ratios of κ = 2 and 4 % is also shown.

In previous years, LEP was operated with a fixed β^* ratio of 0.04 (5 cm vertically over 1.25 m horizontally). In 1993, the β_x^* was kept fixed from injection into physics at a value of 2.5 m. The maximum horizontal β in the superconducting quadrupoles close to the experiments is reduced, resulting in lower background and very stable running conditions for the experiments. A vertical β_y^* of 5 cm was used in physics.

The change in β ratio from 0.04 to 0.02 implies smaller vertical beam sizes for the same luminosity. To keep beam-beam tune shifts equal in both planes, the emittance ratio must equal the beta ratio. In 1993 this implied an emittance ratio of 2 % while in previous years 4 % was sufficient. This is illustrated as lines in fig. 3.

4 PERFORMANCE OPTIMIZATION IN OPERATION

LEP performance with the pretzel scheme and the decreased beta* ratio was very sensitive to a variety of optimization techniques. These optimizations could make a difference of a factor of two in luminosity obtained for a given current, as can be seen in the spread of measured tune shift parameters in fig. 3. On top of the techniques established during 4 on 4 running with the low emittance optics last year, such as emittance control using a wiggler, new procedures were needed in 1993 to fully exploit the pretzel scheme.

The horizontal pretzel orbits are produced using 8 unipolar electrostatic separators. The standard gap size is 12 cm and they were operated with a tension of 120 kV, thus producing a field of 1 MV / m. The gap size of

	1990		1991		1992		1993	
Hours scheduled for machine development	689		997		935		709	
Hours scheduled for physics	2504		2762		3439		2943	
Hours of beam in coast	1048		1242		1742		1619	
Efficiency	43 %		45 %		51 %		55 %	
Integrated luminosity, pb^{-1}	7.6		17.3		28.6		40	
β_x^*, meter	1.25		1.25		1.25		2.5	
β_y^*, cm	7, 5, 4.3		7.5, 5, 4.3		7, 5		5	
Total number of coasts	143		154		199		168	
Percentage of coasts lost	33%		36%		36%		37%	
	peak	avg.	peak	avg.	peak	avg.	peak	avg.
Total current in mA at 20 GeV, 4x4 bunches	4.2	3.1	4.3	3.5	4.5	3.2		
Total current in mA at 20 GeV, 8x8 bunches					5.7	4.7	5.8	4.8
Current in collision at 45 GeV, 4x4 bunches	3.6	2.5	3.7	2.8	4	2.4		
Current in collision at 45 GeV, 8x8 bunches					5	4.2	5.5	4.4
Filling time, hours:minutes	1:20	6:57	1:20	3:07	0:50	2:12	0:54	2:26
Coast duration, hours:minutes	22:35	7:30	27:00	8:00	26:30	8:35		9:40

Table 1: Comparison of LEP performance from 1990 to 1993

each of the 8 separators can be adjusted by remote control. This, together with an additional trim separator is used to minimize the horizontal separation and to maximize luminosity. These adjustments were done to a large extend empirically, looking at beam size and luminosity. A good set of gap trims was found early in the year. Minor readjustments were done later.

The vertical separation is minimized for each experiment using electrostatic trim separators. For 4x4 operation, the trims typically corrected for offsets of 4 μm or less at the interaction points and one set of trims remained optimal over several weeks of running. In the 1993 running in the pretzel scheme, vertical offsets could exceed 10 μm. Readjustments of 1-2 μm per point were necessary on a fill by fill base to assure best luminosity performance.

Even with minimized vertical and horizontal separation, significant variations ($\pm$ 30 %) of vertical tuneshifts and therefore luminosity were observed depending on the vertical orbit. It was not sufficient to reach a small overall rms in the vertical orbit. Correcting back to the particular structure of a vertical orbit saved in a condition with excellent vertical beam-beam tuneshift ("golden orbit") gave reproducibly good results. Following this observation, the technique of correcting towards a "golden orbit" was used regularly and very successfully during the last two month of operation in the year.

As can be seen from fig. 3, the vertical beam-beam tune shift exceeded values of 0.03, very close to the best performance in 4x4 operation. This demonstrates, that running in the pretzel scheme does not only increase the total current, but that this increase can be directly transformed into a gain of luminosity.

Variations of the tunes and chromaticity had little effect on luminosity but could be very important for beam lifetime at the beginning of a coast. For the chromaticity, good stability was found by starting initially with a small positive value (Q' about +2 in both planes). When beams were brought into collisions, coherent oscillations were observed occasionally and could be cured by a small increase of chromaticity. The emittance wiggler was used with full excitation to bring beams into collisions. At progressively reduced levels, the wiggler was also used during the first hours of coasts with high bunch currents to avoid beam-beam flip-flop and bad lifetimes.

5 SUMMARY

LEP was operated very successfully in 1993, delivering a total integrated luminosity of 40 pb^{-1} to each of the four experiments. Using the pretzel scheme, the number of bunches in LEP was doubled from 4x4 to 8x8. The total current was increased by about 60 %. Tuning was more difficult than for operation with 4x4 bunches. By minimization of the horizontal and vertical separation and careful adjustment of the vertical orbit it was possible to transmit most of the gain in total current into a similar gain in luminosity.

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