LEP PERFORMANCE AT 91.5 GEV

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Abstract

The 1997 LEP collider run was the first year of the LEP2 program devoted to stable high luminosity running. The good performance of the LEP superconducting RF system allowed to run at beam energies of 91.5 GeV. In addition to the usual optimisation procedures to minimise the vertical beam emittances, the horizontal beam sizes were reduced by increasing the horizontal damping partition number and reducing the betatron function at the interaction points. Vertical beam-beam tune shifts in excess of 0.05 were achieved with total beam currents of 5 mA. The total integrated luminosity of 73 pb^{-1} is the highest ever recorded in a single year of LEP operation.

1 BEAM ENERGY AND RF

During 1997 LEP was operated routinely at 91.5 GeV. The choice of the energy was dictated by the available total RF voltage. The design gradient of 6 MV/m for the 224 superconducting Nb/Cu cavities was generally met. Taking into account those design fields and the gradients provided by the copper RF system, the total voltage that could be delivered was 2650 MV. In practice about 95% of the voltage, 2540 MV, was available for operation. This would allow for a trip of a high voltage power converter, which supplies 16 cavities, without losing the beams at 91.5 GeV. Such severe trips accounted for about 7% of all RF trips. The mean time between trips increased from about 50 to 70 minutes in the course of the run. 10% of the LEP fills were lost due to RF trips.

2 LEP PERFORMANCE IN 1997

To maximise the performance of LEP the bunch currents are first increased until the beam-beam limit is exceeded with 4 bunches per beam. Then the number of bunches is increased to 6 or 8 per beam as long as they are no limitations to the total beam currents.

In 1997 LEP ran with 4 bunches per beam and a total current around 5.5 mA, because the available cryogenics power prevented running with much higher total intensities. Significantly higher beam currents would have been required to reach equivalent performance with 6 or 8 bunches per beam, making life difficult for the RF and the vacuum systems.

Total beam currents of 5.4 mA, limited by synchro-betatron resonances, were typically accumulated at injection into 4 bunches per beam. In collisions the total current was usually 5.0 mA at the start of fill, the ramp transmission efficiency being 90%. Those currents were about 20% larger than in 1996 thanks to a reduction of the transverse impedance due to the replacement of copper RF cavities by superconducting cavities.

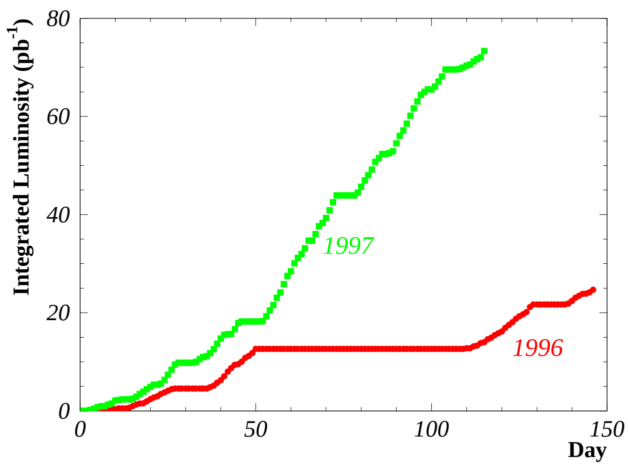

Figure 1: Evolution of the integrated luminosities during the 1996 and 1997 LEP runs. When the best periods of the two runs are compared, the slope for 1997 is a factor 2.3 steeper than for 1996.

During 1997 LEP delivered a total integrated luminosity of 73.3 pb^{-1} (Figure 1). 63.8 pb^{-1} were produced at beam energies ranging from 90.5 to 92 GeV, with 92% of the luminosity delivered at 91.5 GeV. The best performance over 24 hours resulted in 1.9 pb^{-1}. Peak luminosities reached $5 \cdot 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ at the beginning of fills and beam-beam tune shifts ξ_{y} beyond 0.05 where recorded. 2.3 pb^{-1} were delivered at 45 GeV for the LEP detector calibrations. A dedicated run at 65 and 68 GeV to check the existence of a signal observed in 1995 by one of the LEP experiments produced 7.3 pb^{-1}. LEP was colliding beams for physics during 44% of the allocated time. 7% of the scheduled time was also used for beam energy calibration. The down time was dominated by vacuum problems caused by the high levels of synchrotron radiation, by the RF and by the cryogenics systems. About 20% of the fills were lost due to equipment failures. The average turn-around time from a beam dump to the next collisions was 108 minutes.

For most of the year LEP was running with an optics having an arc phase advance per cell of 90° in the horizontal and 60° in the vertical plane (90/60). For the last 10 days

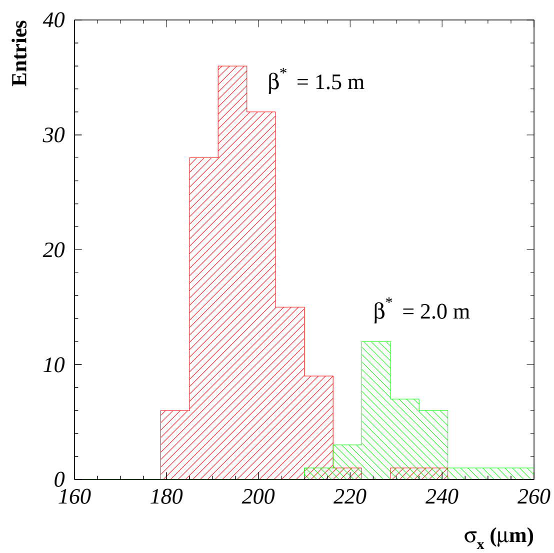

Figure 2: Horizontal beam sizes σ_x measured with beam-beam deflections scans for β_x^* = 1.5 and 2.0 m ($J_x = 1.6$). The mean ratio is 1.15 as expected from the β_x^* ratio.

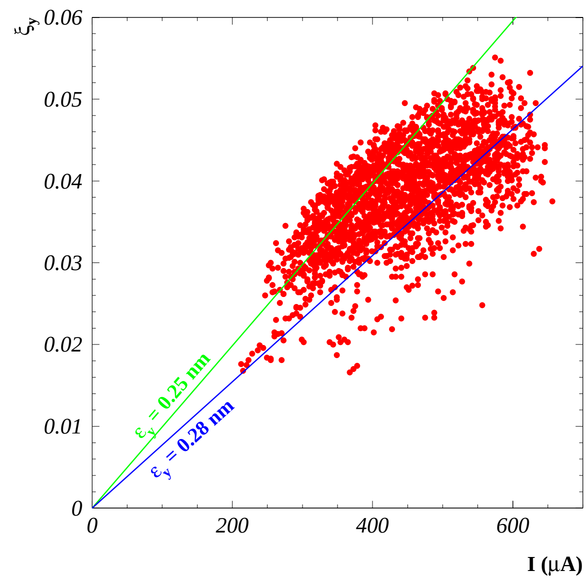

Figure 3: Vertical beam-beam tune shift ξ_y as a function of the bunch current (β_x^* = 1.5 m). There is no strong evidence for a beam-beam limit. The lines show the expected dependences for two vertical emittances ε_y.

a 102/90 optics yielding smaller horizontal emittances was tested in operation. The performance reached levels similar to the 90/60 optics and the integrated luminosity delivered with the 102/90 optics was 2.5 pb^{-1}. This optics will be used for operation in 1998.

3 BEAM SIZE OPTIMISATION

In e^+e^- storage rings the dependence of the horizontal beam emittance ε_x on the beam energy E and on the horizontal damping partition number is

$$\varepsilon_x \sim \frac{E^2}{J_x} \quad (1)$$

for a given optics and phase advance in the arcs. The natural increase of ε_x with beam energy leads to higher backgrounds in the experiments and lower luminosities. To reduce the impact of the emittance increase, J_x was shifted from the usual value $J_x = 1$ to $J_x = 1.6$. This change was obtained with a +120 Hz change of the RF frequency. Since the change of damping partition number also increases the beam energy spread, a higher RF voltage is required for the same beam energy to guarantee a sufficient quantum lifetime. At LEP the top beam energy being limited by the available RF voltage, the beam energy must be reduced by about 0.4 GeV with respect to $J_x = 1$ to guarantee a sufficiently large quantum lifetime of the beams.

A further reduction of the horizontal beam size was obtained by squeezing the horizontal betatron function at the interaction points β_x^* from 2.0 to 1.5 m. Figure 2 shows the horizontal beam sizes at the interaction points for β_x^* of 2.0 and 1.5 m and $J_x = 1.6$. Backgrounds in the experiments did not increase significantly.

The J_x and β_x^* changes resulted in an increase of the luminosity of about 1.45 with respect to 1996. The natural increase of ε_x between 86 and 91.5 GeV leads at the same time to a 6% luminosity reduction. The overall improvement of roughly a factor 2.3 in luminosity production rate compared to 1996 seen in Figure 1 is also due to 20% higher average bunch currents (factor 1.5) and to a faster turnaround time.

To ensure small vertical beam sizes in collision the coupling between the horizontal and vertical planes is carefully adjusted with skew quadrupoles. The amount of coupling is measured at LEP by the closest tune approach [1]. It is corrected during the LEP startup period down to the measurement resolution.

The performance is steadily improved during the run with the help of "Golden Orbits" [1]. Such orbits give reproducible high performance with optimum vertical emittance ε_y and are obtained by trial and error using various orbit correction algorithms. In 1997 the smallest emittances of ε_y = 0.25 nm corresponded to vertical beam sizes of 3.5 μm at the interaction points. When the coupling between the two planes is well corrected, ε_y seems to be limited by the residual vertical dispersion and beam-beam effects. This minimum of ε_y varies from one running period to the next at energies above 80 GeV. The smallest value of ε_y = 0.15 nm was measured in 1996.

Figure 3 shows the correlation between the vertical beam-beam tune shift ξ_y and the bunch currents for all LEP fills with β_x^* = 1.5 m. Although there is a slight levelling of at high currents, there is no strong evidence that the beam-beam limit has already been reached.

Single beam lifetimes at high energy are, for good vac-

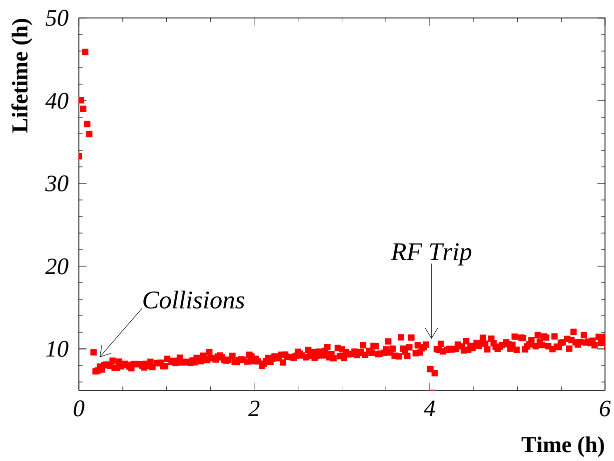

Figure 4: Evolution of the beam lifetime during a physics fill at 91.5 GeV. The initial lifetime is $\sim$ 40 hours. The sudden drop below 10 hours occurs when the beams are brought into collision. The lifetime increases with time as the bunch currents and the beam-beam tune shifts go down.

uum conditions, limited to $\sim$ 40 hours by Compton scattering on thermal photons [4]. In collisions the lifetimes are dominated by beam-beam bremsstrahlung and are inversely proportional to ξ_y. Figure 4 shows the evolution of the beam lifetimes at 91.5 GeV.

4 OPTIMISATION TOOLS

Vertical collision offsets between the beams are corrected with beam-beam deflection scans [2]. The beam-beam kick between the 2 beams in collision is reconstructed from the closed orbit readings and measured for each IP as a function of the vertical separator settings which are used to create a closed local bump around the IP. An example of a scan, which takes about 4 minutes, is shown in Figure 5. The stability of the offsets is 1-2 μm over a few weeks, to be compared with beam sizes of 4 μm.

Once the collision offsets are corrected, the beam-beam tune shifts ξ_y are optimised using either the luminosity measurements or beam size signals from various LEP emittance measurement devices. Even when the absolute emittance values are not very accurate, the relative signals give valuable information for machine tuning.

In the later part of the 1997 run first attempts were made to measure continuously the various beam-beam modes and in particular the σ and π modes using a small but controlled excitation of the beams [3]. This instrument will be further developed in the future and promises to become a good tool for performance optimisation.

5 ENERGY CALIBRATION

A large amount of time was devoted to improve the knowledge of the beam energy at high energy. For LEP200 the beam energy is obtained by interpolation up to 91.5 GeV of precise resonant depolarization calibrations in the range of

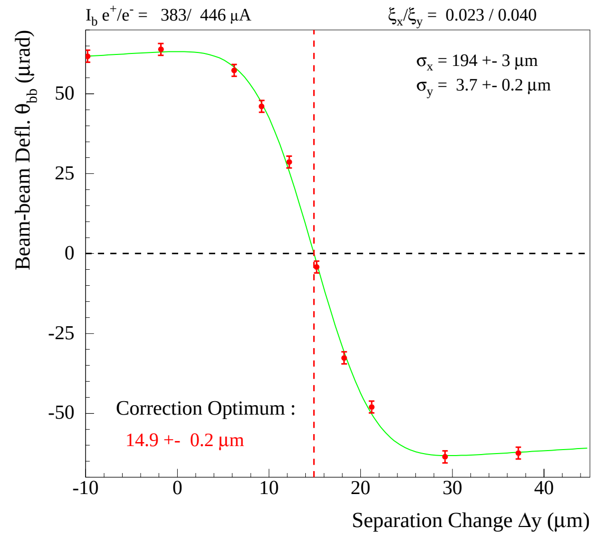

Figure 5: Example of a beam-beam deflection scan used to optimise the setting of the vertical separators. The beam sizes at the collision point σ_x and σ_y as well as the beam-beam tune shifts ξ_x and ξ_y are extracted from the fit to the data (line).

40 to 55 GeV using Nuclear Magnetic Resonances probes and flux measurement loops. The accuracy of this procedure depends on the highest energy at which resonant depolarization is possible as well as on the lever arm of calibrated energies. Between 1996 and 1997 the lever arm was increased from 5 to 14 GeV and the highest calibrated energy was increased from 50 to 55 GeV [5].

6 CONCLUSION

Higher bunch currents and smaller horizontal beam sizes made it possible to boost the LEP performance by more than a factor two between 1996 and 1997. Record beam-beam tune shifts over 0.05 were observed. A further reduction of the transverse impedance in 1998 and the use of an optics with smaller horizontal emittance could further improve the performance in the coming years.

7 REFERENCES

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