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LUMINOSITY AND BEAM MEASUREMENTS USED FOR PERFORMANCE OPTIMISATION IN THE LEP COLLIDER

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The vertical beam-beam parameter in LEP reached 0.083 in 1999. In order to achieve and maintain this high performance a number of different observables are continuously monitored and optimised. The beam sizes are measured using X-ray detectors and UV telescopes. The luminosity is determined directly with tungsten-silicon calorimeters and indirectly through an accurate measurement of the beam lifetime. The tune shift is measured from the tune spectrum in collision. Beam-beam deflection scans provide information about the beam sizes and separation at the interaction points. The different measurements are shortly reviewed and their resolution and time response is analysed. Their use for the optimisation of LEP is described.

1 INTRODUCTION

The magnitude of unavoidable machine imperfections and the efficiency of correction methods determine the vertical emittance in LEP. Ideally it can be reduced to a small residual value, that is in practice limited by the beam-beam interaction. The empirical fine-tuning of LEP involves more than a dozen methods/knobs, relying on fast and accurate performance measurements [1,2]. Table 1 summarises some relevant beam and performance parameters for LEP operation.

Table 1: LEP performance and basic beam parameters for high energy running in 1999 and 2000.

Parameter	Value
Bunch current	400-800 μA
Beam energy	98-104.4 GeV
Repetition frequency	11245.5 Hz
Number of bunches	4 per beam
Horizontal emittance	~ 45 nm
Vertical emittance	80-400 pm
Max. beam-beam parameter	0.083
Max. luminosity	10^{32} cm^{-2} s^{-1}

2 BEAM DIAGNOSTICS

Beam size monitoring

The BEUV telescopes detect the synchrotron light emitted by the beam in the near ultra-violet [3]. It provides a real time 2D image of the beam, integrating over 224 turns and all bunches in the storage ring. Diffraction and deformations of the mirror limit its absolute precision in emittance to ~ 0.25 nm. The BEUV image is used for horizontal beam size measurement and for real-time observation of beam shape.

The BEXE detectors observe the synchrotron light in the X-ray range [4], providing a measurement of the local vertical beam size σ_y. A "turn average display" shows a 25-turn average of σ_y every second, with a precision of ~1 % for σ_y down to 300 μm [4]. The vertical beam size can also be measured turn-by-turn for a selected bunch in the machine. The BEXE is used extensively for emittance optimisation, however, its resolution becomes limited for the smallest vertical beam sizes (~100 μm).

Collision offset monitoring

Beam-beam deflection scans are used to measure the collision offset and the convoluted beam sizes at the IP [5]. A scan takes about 20 minutes per IP and the accuracy in the convoluted beam size is about 10%. The BBDS is used to optimise the beam-beam overlap and to detect local problems in the beam size, e.g. due to errors in the IP beta functions.

Luminosity monitoring

The LEP experiments measure local luminosity. The numbers are calibrated with the measured cross-sections and therefore quite accurate. However, the short-term resolution is limited with a time response of ~4 min.

LEP luminosity monitors: The LEP luminosity monitors which consist of 16 Tungsten-Silicon calorimeters detect Bhabba scattering events [6]. The high-energy resolution is limited due to higher background rate and smaller cross section, if compared to 45 GeV.

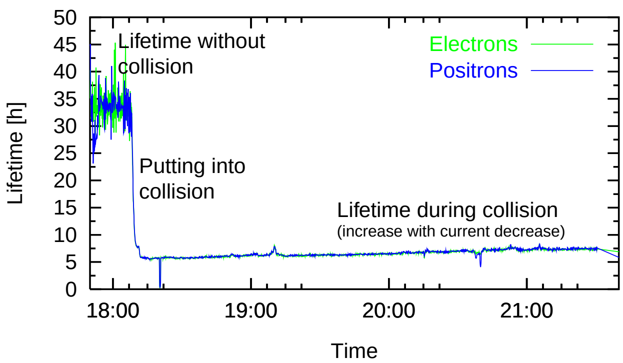

Figure 1: Evolution of beam lifetime in LEP.

Luminosity from lifetime: The beam current lifetime τ in collision is limited by beam-beam bremsstrahlung (low angle Bhaba scattering) at the highest LEP energies [7]. In particular there is no significant effect of beam tails. The average luminosity L can then be written as:

$$\frac{L}{10^{30}(\mathrm{cm}^{-2}\mathrm{s}^{-1})} = 671.2 \cdot \frac{i_b}{(\mathrm{mA})} \cdot \left(\frac{(\mathrm{h})}{\tau} - \frac{(\mathrm{h})}{\tau_0} \right) \quad (1)$$

with i_b being the bunch current and τ_0 the lifetime without collisions (from Compton scattering on thermal photons, beam-gas scattering). Figure 1 shows the beam lifetime during a fill measured by the bunch current transformer (BCT). A fast online measurement of the average luminosity, based on beam lifetime, was implemented for the 1999 run [8] with a resolution of ~2% for a 30 s running average. This performance results from the improved signal to noise ratio of 95-105 dB achieved in 1999 for individual bunch current measurements made at a rate of 2 Hz.

Beam-beam tune shift from σ–π mode: The vertical tune spectrum in collision exhibits peaks at the σ and π-modes. The tune difference ΔQ_v between the two modes is roughly proportional to the vertical beam-beam parameter ξ_v (and thus to average luminosity). The approximate relationship $\xi_v \approx \Delta Q_v/4$ is being used to calculate ξ_v per IP. A continuous measurement of the σ–π mode was implemented for the 1999 run, allowing a fast online tracking of ξ_v [9]. A measurement is available every 3 s with a resolution of ~2% in ξ_v. The method always works reliably with bunch currents below 450 μA. The tune locks can be lost for higher intensities, limiting the range of usability for luminosity optimisation.

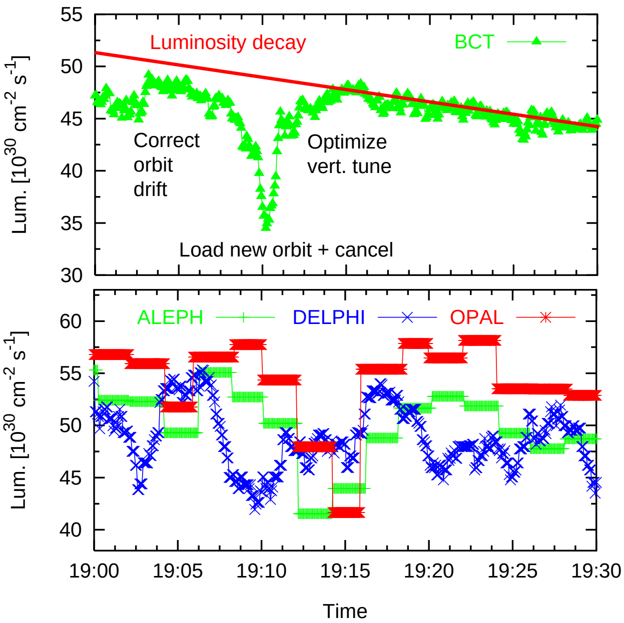

Figure 2: Example of luminosity tuning as observed with the current lifetime (BCT) and the experiments (ALEPH, DELPHI and OPAL; L3 was off).

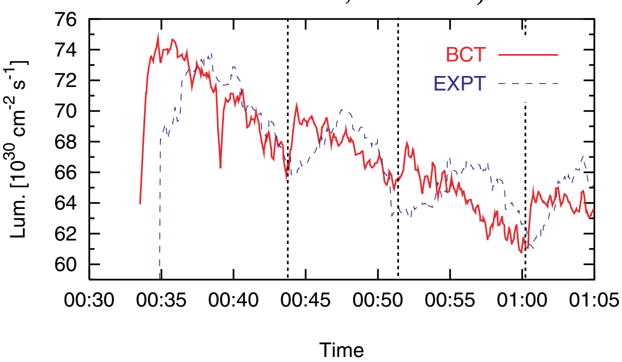

Figure 3: Comparison of the average luminosity from the experiments (EXPT) and the beam lifetime (BCT).

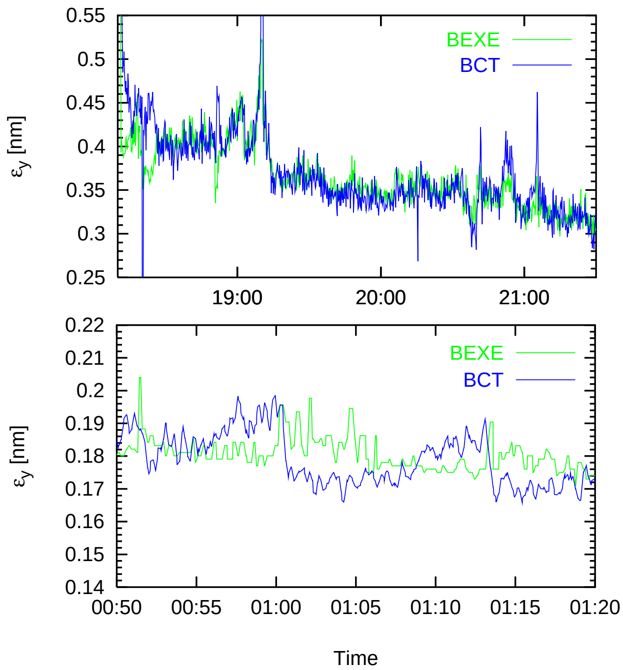

Figure 4: Comparison of vertical emittance from the BEXE beam size measurement and the BCT luminosity.

3 LEP ONLINE TUNING

The LEP performance during physics fills is optimised by reducing the vertical emittance with corrections of coupling, the tunes, the vertical orbit and dispersion. More than a dozen different methods/knobs are used to that purpose. The optimum performance can only be achieved if small luminosity improvements are detected,. Figure 2 shows an example of luminosity optimisation with vertical orbit and tune. The luminosity changes are easily visible from the current lifetime (BCT). The experimental luminosities show a large spread.

The average luminosity from the four experiments shows a significantly smaller spread and in Figure 3 it is compared to the BCT luminosity for a fill at an energy of 101 GeV. The luminosity improvements (indicated by dashed lines) are due to automatic corrections from the vertical orbit feedback. The two luminosity signals are in excellent agreement and show both the beneficial effect of the orbit feedback. The response of the lifetime signal is, however, much faster (30 s compared to 4 min). The measurement in Figure 3 can be used to estimate the luminosity and vertical emittance drift due to uncontrolled changes in the vertical orbit:

$$\Delta L \approx 0.3\ 10^{30}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1},$$

$$\Delta\varepsilon_y \approx 0.002\ \mathrm{nm} \qquad \text{per minute.}$$

In order to calculate the vertical emittance from the measured luminosity the design betatron functions and the design horizontal emittance are assumed (taking into account J_x). We can then convert the BCT lifetime into vertical emittance ε_y and use it to calibrate the BEXE measurement of vertical beam size σ_y in terms of emittance:

$$\sigma_y^2 = C\beta_y \cdot \varepsilon_y + \sigma_0^2$$

(2)

Fits to 1998 and 1999 data give $C\beta_y$ = 0.6/1.0 m and σ_0 = 292/283 μm. The fit results are in agreement with the expectation. The vertical emittance is shown in Figure 4 for data from 1998 (top) and 1999 (bottom). The emittance is calculated from the BCT luminosity and from the BEXE measurement of vertical beam size. As the BEXE data is calibrated with the BCT data and Equation 2, we expect a general agreement. We do indeed find an excellent agreement for the larger emittance in 1998. The two signals track very well, even for short-term variations.

The data shown for 1999 (Figure 4, bottom) corresponds to the data shown in Figure 3, where the BCT and the experimental data are in good agreement. For the smaller 1999 emittance the BEXE beam size measurement cannot resolve the short-term variation as seen by the BCT lifetime and the experiments. The limitation in resolution becomes understandable if the local beam size (~100 μm) is compared to the constant term σ_0 in Equation 2 (~300 μm). In addition, the relationship between local beam size and emittance may be perturbed, for example by beta beating.

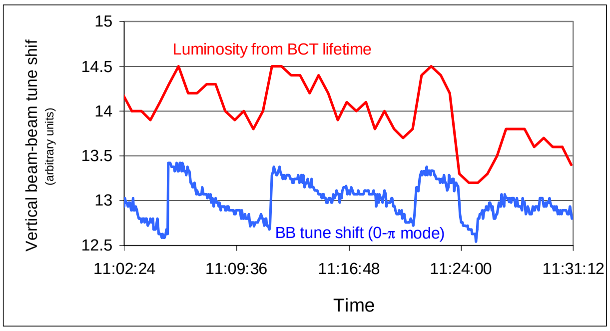

Figure 5: Measured beam-beam tune shift from the σ-π mode and luminosity from the BCT versus time.

A measurement of the vertical beam-beam tune shift from the σ-π modes in the tune spectrum is shown in Figure 5. The signal shows a fast response to change in luminosity. The time resolution is only 3 s, compared to 30 s for the BCT signal. The relative resolution in luminosity is about 2% for both. The measurement of the σ-π modes provides a very fast and accurate tuning signal. However, the measurement is not fully operational, as it requires manual set-up at the beginning of each fill. In addition, the tune locks can be lost with a more noisy tune spectrum for bunch intensities above 450 μA.

4 CONCLUSION

A number of dedicated beam diagnostic devices around the LEP ring provide fast online tuning signals for the empirical optimisation of the LEP performance.

Imaging telescopes (BEUV) look at synchrotron light in the UV range and provide a real-time 2D image of the beam and horizontal beam size measurements.

Optimisation of the vertical emittance during high-energy physics fills relies mainly on the vertical beam size measurement from X-ray synchrotron light (BEXE), the luminosity provided by the experiments and the luminosity estimates from the current lifetime (BCT) and the σ–π modes. The two later signals were newly implemented for the 1999 run. The time response is slow for the experiments (~4 min), faster for BEXE (1 s), BCT (30 s), and σ-π modes (3 s). The BEXE resolution for the smallest vertical emittances (< 0.25 nm) becomes insufficient for fine-tuning. BCT and σ-π modes provide sufficient resolution (ΔL/L ≈ 2%). Especially the use of the BCT measurement was essential for achieving the high performance in 1999 with a vertical beam-beam parameter of up to 0.083.

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