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BEAM-BEAM INTERACTION AND BEAM LIFETIME IN LEP

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ABSTRACT

LEP has been operated at beam energies around 45 GeV, 65 GeV and 90 GeV, thus covering a factor of two in beam energies. Vertical beam-beam tune shifts exceeding 0.04 were reached at all energies.

At the lower energies, emittance increase using wiggler magnets was used successfully to avoid excessive beam blow-up and flip-flop from the beam-beam interaction and allowed to operate safely at the beam-beam limit throughout fills lasting typically 10 hours. Significant non-Gaussian tails were observed in the vertical plane and have limited the maximum current in collisions.

At higher energies, the best performance in terms of luminosity and beam-beam tune shift demands higher currents per bunch and minimization of emittances. Vertical to horizontal emittance ratios below 0.5 % have been achieved.

In stable running conditions, beam lifetime in LEP can be accounted for by three scattering processes: Beam-beam Bremsstrahlung, Compton scattering on black-body photons and beam-gas Bremsstrahlung.

1 Introduction

There was enough time (1.5 hours) and interest in LEP experience in the beam-beam working group to present a detailed review. Only a short summary is given here. More details[1] can be found in 1) and a more general discussion in 2).

LEP operates with a small number of bunches (4 to 12 per beam). The intensity per bunch is rather high (up to 0.7 mA or $3.9 \cdot 10^{11}$ particles per bunch). Beams collide head-on without crossing angle and the interaction regions are designed to be dispersion free. The vertical β-function at the interaction point is $\beta_y^* = 5$ cm. LEP uses flat beams and the vertical emittance can be as small as 0.1 nm.

2 LEP1, E = 45.6 GeV

LEP was operated in the years 1989 to 1995 at beam energies close to 45.6 GeV for the production of Z-bosons 3). LEP is still operated one to two weeks per year at 45.6 GeV to provide the experiments with Z events for calibration purposes.

It took several years until beam-beam tune shifts exceeded values of 0.04. One improvement introduced in 1992 was emittance control: The phase advance per standard FODO cell was increased from 60° to 90° which reduced the horizontal emittance from 35 to 12 nm. Using a wiggler magnet in a dispersive region, the horizontal emittance was now adjustable in the range from 12 to 36 nm. It was found that at LEP1 energies, high horizontal beam-beam tune shifts (exceeding 0.04) with significant horizontal emittance blow-up would lead to high backgrounds in the experiments and sometimes beam lifetime problems. This was avoided using controlled horizontal emittance increase during the first hours of fills, when currents per bunch were high. There was no need to artificially increase the vertical emittance.

Until 1992, LEP was filled with 4 electron and 4 positron bunches. Local vertical separation was used to avoid unwanted collisions. From 1993 on, regular operation was using 8 bunches per beam with horizontal separation in the arcs of LEP using the Pretzel scheme. Operation and tune control became more critical and lifetime and background problems tended to start at somewhat lower bunch currents. After some time of careful adjustments and minimization of the residual horizontal separation (in addition to the minimization of the vertical separation that is frequently done in LEP) it was possible to reach again high vertical beam-beam tune shifts. β_x^* was increased from 1.25 and 2.5 m to reduce background to the experiments. This did not affect the performance in terms of the maximum vertical beam-beam tune shift ξ_y that could be reached.

Good control of many parameters is necessary to obtain high beam-beam tune shifts:

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[1] Reference 1) and other related papers can be accessed via http://wwwcn.cern.ch/~hbu/

- make sure the machine is generally well adjusted, in particular check β^*
- minimize coupling
- realignment in the vertical plane once per year
- scan/minimize vertical separation regularly (with Pretzel also horizontal separation) using luminosity or beam-beam deflection scans
- choose a good working point, both for luminosity and lifetime/background
- correct the closed orbit frequently, use "golden" reference orbit

"Golden orbits" are obtained empirically, starting from a well corrected machine with minimized rms orbit. The vertical orbit is then modified by many small local and global vertical corrections. The effect on luminosity can still be as much as 30 %. Whenever a particularly high beam-beam tune shift or specific luminosity is reached, the orbit is saved and can serve as new reference "golden orbit". The ingredients of a "golden orbit" are not exactly known, but certainly include a minimization of the vertical dispersion at the interaction points and of the coupling between the horizontal and vertical plane.

Differences in intensities between the various electron and positron bunches up to a level of about 10 % did not cause any problems.

There is some emittance increase or loss in luminosity but no major problem when beams collide with some offset. Beams can be brought slowly into collisions and the residual separation safely be scanned at individual collision points.

The performance in terms of vertical beam-beam tune shift decreased in 1995 when 12 bunches per beam were collided using bunch trains with vertical separation. This was attributed to residual vertical separation, that could not simultaneously be minimized for all three bunches in a train.

3 LEP1.5, E = 65 GeV

Following the installation of more superconducting radio frequency cavities, the beam energy in LEP was raised in November 1995 to 65 GeV. The same optics (90°/60°) was used as previously at LEP1 energies. The natural horizontal emittance at 65 GeV is then about $\varepsilon_x = 25$ nm. New record levels in beam-beam tune shift ($\xi_y = 0.05$) and peak luminosity ($\mathcal{L} = 2.6 \cdot 10^{31} \mathrm{cm}^{-2}\mathrm{s}^{-1}$) with only 4 bunches per beam were obtained within 10 days of operation at this new energy.

Fig. 1 shows the vertical beam-beam tune shift for a fill at 65 GeV. If we extrapolate the $\kappa = 0.5$ % line in Fig. 1 we obtain an unperturbed vertical beam-beam tune shift of about 0.08 at a current of 0.5 mA. The size of both beams increased rather symmetrically in the vertical plane. In the horizontal plane, the

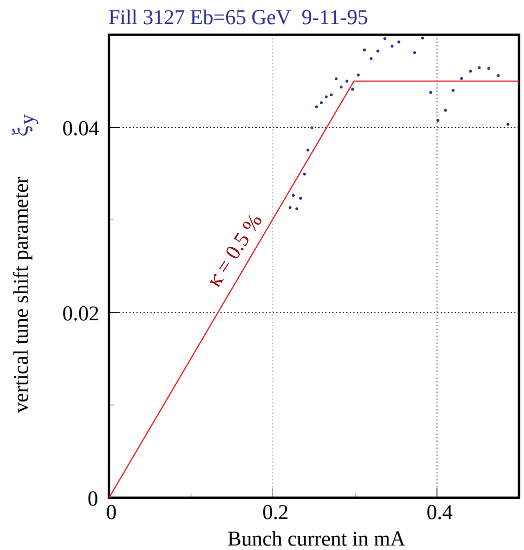

Figure 1: *ξ_y dependence on bunch current observed at a beam energy of 65 GeV. The data is shown as dots and the expected behavior for an emittance ratio κ=0.5% and a maximum ξ_y=0.045 as line.*

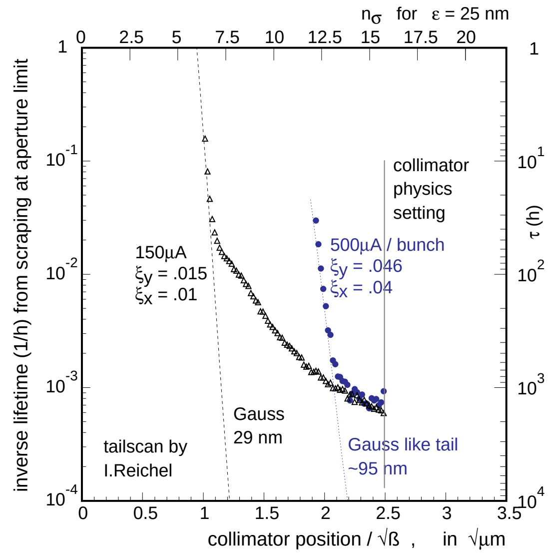

Figure 2: *Observed horizontal beam tails at 65 GeV for low and high horizontal beam-beam tune shift.*

emittance as observed by the synchrotron light monitor increased only by about 10 % when beams were brought into collision. The horizontal beam-beam tune shift parameter reached about $\xi_x = 0.04$. Figure 2 shows horizontal tail scans done at 65 GeV. A strong tail at about 12 σ_x from the core emittance was observed for high horizontal beam-beam tune shift, but did not yet cause significant lifetime or background problems.

4 LEP2, E $\approx$ 90 GeV

After adding many more superconducting cavities in the shutdown between 1995 and 1996 and in a short stop in summer 1996, it was possible to raise the beam energy to 86 GeV. The natural horizontal emittance at this energy is $\varepsilon_x = 42$ nm for the $90^\circ/60^\circ$ lattice. Vertical emittances down to 0.1 nm corresponding to an emittance ratio of only 0.25 % were obtained and vertical tune shifts reached $\xi_y = 0.04$ without signs of saturation.

After further installation of superconducting cavities, the beam energy was raised in 1997 to 91.5 GeV. The horizontal emittance was decreased to about

30 nm using a horizontal damping partition of J_x =1.6. Vertical tune shifts regularly exceeded 0.04 and started just about to saturate at values of $\xi_y = 0.05$.

Some weeks of regular operation were spent using a 108°/90° and 102°/90° lattice. The 102°/90° lattice has a natural emittance of 37 nm at 91.5 GeV. Using a damping partition of $J_x = 1.6$ (such that the emittance is reduced to 23 nm) it was possible to reach and maintain for some time a vertical beam-beam tune shift of $\xi_y = 0.05$. Lifetime problems due to scraping into non-Gaussian tails were avoided by optimization of the working point and reduction of chromaticities to $Q' \approx 1$.

5 Beam Tails

At a low level, non-Gaussian tails were observed in LEP both in the horizontal and the vertical plane even without collisions. They can be explained to a large extent by scattering processes and off-momentum particles as described in [4) 5)]. The amount of non-Gaussian tails can increase significantly for high currents and high beam-beam tune shifts. High chromaticities can further enhance tails, as can be seen in Fig. 3.

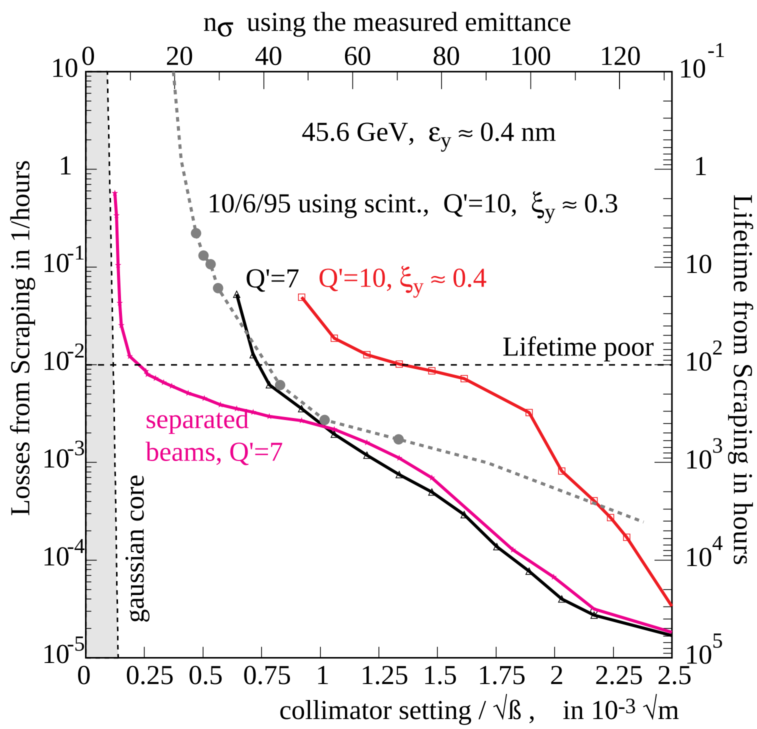

Figure 3: *Measured beam tails in the vertical plane.*

The presence of strong non-Gaussian tails, mainly in the vertical plane, can result in background spikes and lifetime problems. This in fact limited the useful current that could safely be collided at LEP1 to about 0.4 mA per bunch.

6 Beam Lifetime

Beam lifetimes in LEP are well understood [6]. Single beam lifetimes are typically 40 hours and mainly due to beam particles lost in Compton scattering on photons, originating from the black body radiation of the beam pipe. In collisions, the lifetime decreases to typically 20 hours at LEP1 and 8 to 10 hours at LEP2. The dominant process is radiative Bhabha scattering (also called beam-beam Bremsstrahlung). The lifetime component due to the e^+e^- collisions is inversely proportional to ξ_y. Additional losses, not accounted for by scattering processes, are sometimes seen at high currents and are attributed to scraping of non-Gaussian tails.

References

1. H. Burkhardt, Energy Dependence of Beam-Beam Interactions at LEP. In: Proceedings of the 17th Particle Accelerator Conference, (1997). To be published.

2. J. Jowett. Beam Dynamics at LEP. These proceedings.

3. G. Arduini *et al.*, LEP1 operation, 1989-1995. In: Proceedings of the 5th European Particle Accelerator Conference (edited by V. Suller and C. Petit-Jean-Genaz), volume 1, 286 (1996).

4. I. Reichel *et al.*. Observation and Simulation of Beam Tails in LEP. These proceedings.

5. I. Reichel, Studies of the Transverse Beam Profile in LEP. Ph.D. thesis, RWTH Aachen, (work still in progress).

6. H. Burkhardt *et al.*, Beam Lifetimes in LEP. In: Proceedings of the 4th European Particle Accelerator Conference (edited by V. Suller and C. Petit-Jean-Genaz), volume II, 1353 (1994).