Luminosity Optimisation Using Beam-beam Deflections at LEP

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Abstract

In maximizing the performance of the LEP electron-positron collider it is important to ensure that the beams collide head-on at the interaction points. The deflection of the beams due to the beam-beam interaction has been measured using orbit monitors located close to the interaction points. The dependence of the beam-beam deflection on the transverse distance between the beams has been used to optimise the overlap of the beams in the vertical plane and to measure the beam sizes at the interaction points.

1 INTRODUCTION

To obtain high luminosities and beam-beam tune shifts the beams should collide with transverse impact parameters that are small compared to the beam sizes at the interaction points (IP). For flat beams this is particularly delicate in the vertical plane where the beam sizes are small. At the e^+e^- collider LEP the overlap of the beams in the vertical plane is optimized with electrostatic separator scans. During such a scan, the vertical separation of the beams is varied in steps with a local electrostatic bump. For each step the luminosity is recorded. The separator setting corresponding to centred beams where the impact parameter is zero corresponds to the highest luminosity. The collision offsets that have to be corrected at LEP are in the range of ± 20 μm at the IP. This is quite large compared to the typical vertical r.m.s. beam sizes of 3 to 6 μm. For beam energies of 45 GeV a scan of one of the four IPs is performed in 5 to 10 minutes. The duration of the scans is dominated by the time required to obtain an accurate luminosity measurement.

An alternative way to centre the beams uses the deflections induced on the trajectories by the electromagnetic interaction between the bunches as the beams pass each other with a non-zero impact parameter. This technique requires accurate measurements of the beam angles at their collision point and has been pioneered at the SLC [2, 3]. Successful attempts to measure the effect of the beam-beam interaction on the closed orbit have also been made at CESR [4] and at KEK [5]. An optimisation of the beam overlap using such a technique has been carried out for the first time at LEP. It relies on the interpolation of the beam position from nearby orbit monitors to the interaction point. This method may turn out to be very useful when LEP will run at beam energies above 80 GeV where lower Bhabha cross-section and higher backgrounds in the luminosity detectors may increase the length of the luminosity scans even further.

We will describe in this publication the method used at LEP to measure the beam-beam deflection and show results of the measurements made during the first LEP high energy run.

2 THE BEAM-BEAM DEFLECTIONS

We will consider only the case of flat beams where at the IP the vertical r.m.s. beam size σ_y is much smaller than the horizontal r.m.s. beam size σ_x. We assume that the transverse and longitudinal charge distributions of the beams are Gaussian and that the r.m.s. bunch length is much larger than σ_y and σ_x. As two bunches pass each other, the horizontal and vertical beam-beam kicks $\Delta x'$ and $\Delta y'$ received by a single particle in one bunch due to the electromagnetic field of the counter-rotating bunch are given by [6, 7, 8, 9] :

$$\left\{ \begin{array}{c} \Delta x' \\ \Delta y' \end{array} \right\} = A \left\{ \begin{array}{c} \Im m \\ \Re e \end{array} \right\} F(x, y, \sigma_x, \sigma_y) \tag{1}$$

where $\Re e$ and $\Im m$ are the real and imaginary parts of the function $F(x, y, \sigma_x, \sigma_y)$:

$$\begin{aligned} F(x, y, \sigma_x, \sigma_y) = {} & w\left(\frac{x+iy}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) \\ & - e^{-(x^2/2\sigma_x^2+y^2/2\sigma_y^2)}\, w\left(\frac{x\sigma_y/\sigma_x+iy\sigma_x/\sigma_y}{\sqrt{2(\sigma_x^2-\sigma_y^2)}}\right) \end{aligned} \tag{2}$$

A is given by :

$$A = -\frac{\sqrt{2\pi} N r_e}{\gamma\sqrt{\sigma_x^2-\sigma_y^2}} \tag{3}$$

N is the number of particle in the bunch, x and y are the horizontal and vertical distances from the test particle to the centre of the counter-rotating bunch. r_e is the classical electron radius and γ is the Lorentz factor. $w(z)$ is the complex error function.

For a particle close to the centre of the other bunch, the beam-beam kick increases linearly with the separation $(u = x, y)$:

$$\Delta u' = -\frac{4\pi\xi_u}{\beta_u^*}\, u \tag{4}$$

and vanishes when the particle is centred ($u = 0$). β_u^* is the betatron function at the IP. The beam-beam tune shift parameters ξ_u are given by

$$\xi_u = \frac{r_e N \beta_u^*}{2\pi\gamma\sigma_u(\sigma_x + \sigma_y)} \tag{5}$$

In the vertical plane the largest deflections occur for $|y/\sigma_y| \approx 2.5$ and can be approximated by

$$|\Delta y'_{\max}| \approx \frac{\sqrt{2\pi} N r_e}{\gamma \sigma_x} \tag{6}$$

when $\sigma_x \gg \sigma_y$. $\Delta y'_{\max}$ can be used to measure the horizontal beam size at the IP since it depends on the bunch population, the beam energy and on σ_x. $\Delta y'$ falls off slowly for large y/σ_y because of the elliptical symmetry of the electromagnetic fields. The effect of a horizontal offset x on $\Delta y'$ is negligible as long as it is small compared to σ_x.

The average kick seen by the whole bunch differs from the kick seen by a single particle [8, 9] and is obtained from Equation 1 by replacing the beam sizes σ_u with the effective sizes $\tilde{\sigma}_u$:

$$\tilde{\sigma}_u = \sqrt{(\sigma_u^+)^2 + (\sigma_u^-)^2} \tag{7}$$

where $+(-)$ labels the positron(electron) beam. The separations x and y represent then the distances between the centres of the two colliding bunches. Since the beam-beam deflection angle is zero is when beams collide without transverse offset, steering the beams to produce no deflection will maximise luminosity.

3 BEAM-BEAM DEFLECTION MEASUREMENTS AT LEP

In order to obtain the spatial coordinates of the beams at the IPs, the beam positions are measured at two beam position monitors (BPM) on each side of the IP and extrapolated to the IP with the optical transfer matrices. The settings of electrostatic separators installed between the BPMs and the IP are also taken into account. On the time scale of one hour, the vertical beam separation can be tracked with this interpolation with an accuracy of about 1 μm. The vertical beam angles can be measured with relative accuracies of a few micro-radians.

To enhance the sensitivity of the measurements, we take advantage of the fact that the beam-beam kicks are of opposite sign for the two beams. For this reason we use the variable θ_{bb} which corresponds to the difference of the deflections of the positron and electron beam :

$$\theta_{bb} = (\theta_L^+ - \theta_R^+) - (\theta_L^- - \theta_R^-) \tag{8}$$

θ is the beam angle at the IP, $L(R)$ labels the Left(Right) side of the IP and $+(-)$ the positron(electron) beam. θ_{bb} is less sensitive to systematics errors of the BPMs and their electronics because it involves only difference measurements.

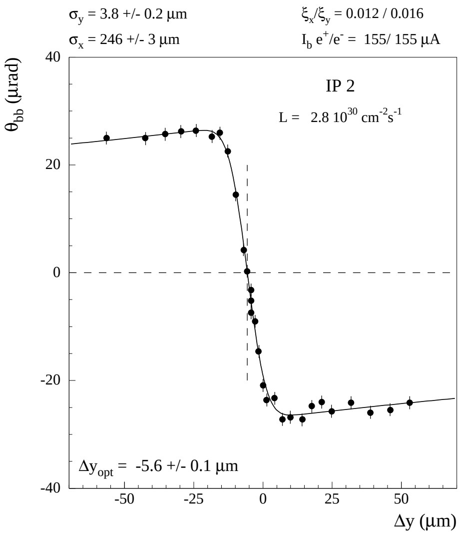

Figure 1: Beam-beam deflection scan for a beam energy of 65.1 GeV. θ_{bb} is shown as a function of the electrostatic separator bump amplitude Δy. The systematic offset θ_0 is already subtracted from the data. The line is the result of the fit. The luminosity L and the beam-beam tune shifts ξ_x and ξ_y have been calculated from the fitted beam sizes and the bunch currents I_b. Δy_{opt} is the optimum separator setting.

Four vertical electrostatic separators are used around each IP to vary the impact parameter of the collisions with a closed orbit bump. The expected change of θ_{bb} can be parameterised by a function $\mathcal{G}$ of the separation bump amplitude Δy using the expressions given in the previous section :

$$\mathcal{G}(\Delta y) = \theta_0 + (A^+ + A^-) \\ \Re e F(x = 0, \Delta y - \Delta y_{\text{opt}}, \sqrt{2}\sigma_x, \sqrt{2}\sigma_y) \tag{9}$$

where we assume here that the beams are centred in the horizontal plane ($x = 0$). Δy_{opt} is the separator bump amplitude for which the beams are centred in the vertical plane. θ_0 is an offset that takes into account measurement systematics of the BPMs. $A^{+(-)}$ is given by :

$$A^{+(-)} = -\frac{\sqrt{\pi} N^{+(-)} r_e}{\gamma\sqrt{\sigma_x^2 - \sigma_y^2}} \tag{10}$$

$N^{+(-)}$ is the average number of particles in the position(electron) bunches which is obtained from the bunch currents. The beam sizes correspond to :

$$\sigma_u = \frac{\tilde{\sigma}_u}{\sqrt{2}} \tag{11}$$

where $\tilde{\sigma}_u$ has been defined with Equation 7. The measured deflections θ_{bb} are fitted with the MINUIT [10] program to the function $\mathcal{G}$ of Equation 9 using as free parameters θ_0, Δy_{opt}, σ_x and σ_y.

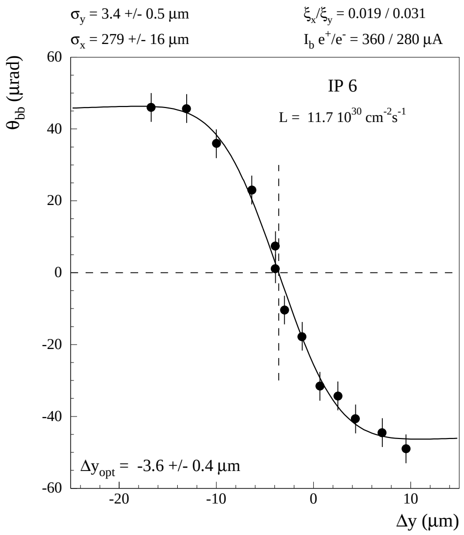

Figure 2: Beam-beam deflection scan performed at a beam energy of 68.1 GeV. The bunch currents are more than twice as large as for the scan shown in Figure 1.

4 RESULTS OF BEAM-BEAM DEFLECTION SCANS

During the 1995 LEP run, scans of the beam-beam deflection angle were performed during normal operation of the collider. The electrostatic separator bumps were varied in steps and for each setting a closed orbit was recorded. The angle θ_{bb} was calculated from the separator kicks and from the beam position at two BPMs on each side of the IP. The resulting data sample was fitted to the function $\mathcal{G}$. The scatter of the data around the fit shows that the measurement accuracies of θ_{bb} are in the range of 1 to 5 μrad. Fits of the e^+e^- difference orbit indicate that the horizontal separation between the beams was on average smaller than 10 μm. The assumption, used in Equation 9, that the beams are centred in the horizontal plane is therefore a good approximation because $\sigma_x \geq 200$ μm. Two examples of scans are shown in Figures 1 and 2. The first scan was performed with low bunch currents. The separation was varied by about 110 μm to test the beam-beam kick parameterisation over a wide range. The agreement between data and model is excellent. An example of a scan with higher bunch currents is shown in Figure 2.

For each scan the optimum settings $\Delta y_{\,\mathrm{opt}}$ corresponds to the point of highest luminosity within about ± 1 μm. In one case a luminosity scan performed just after the beam-beam deflection scan gave the same value for $\Delta y_{\,\mathrm{opt}}$ within the errors of the fits. More comparative studies between beam-beam deflection and luminosity scans will be made in the future to evaluate more precisely the systematic errors on $\Delta y_{\,\mathrm{opt}}$.

From the bunch currents and the beam sizes the expected luminosity is easily evaluated :

$$L = \frac{kN^+N^-f}{4\pi\sigma_x\sigma_y} \tag{12}$$

k (4) is the number of bunches per beam and f $(11.25$ kHz) is the revolution frequency. For all scans the luminosity calculated from the fitted beam sizes and the bunch currents agrees within about 10% with the luminosity measured by the corresponding LEP experiment when the separators were set to $\Delta y_{\,\mathrm{opt}}$. These beam size measurements at the IP are an interesting side product of the scans. During the scans, the beam sizes change slightly due to the beam-beam interaction, particularly for separations in the range $1 \leq |y|/\sigma_y \leq 3$, leading very often to “flip-flop” situations with asymmetric beam sizes of the electron and positron beams. These effects are not large enough however to perturb the fits very significantly.

5 CONCLUSIONS

Scans of the vertical beam-beam deflections have been performed successfully at LEP. Thanks to the very good performance of the BPMs, such scans provide measurements of the collision impact parameter with an accuracy of at least 1 μm at the IP. Luminosities predicted with beam sizes extracted from the fits agreed well with direct measurements by the experiments.

In the future it is planed to increase the speed of the scans using an automatic procedure and a faster orbit acquisition. The duration of a beam-beam deflection scan would then be reduced to less than 3 minutes, compared to probably more than 15 minutes for a luminosity scan. This would make these scans very useful optimisation tools when LEP will be running at beam energies above 80 GeV.

6 REFERENCES

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