EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN - SL DIVISION

SL/Note 96-01 (OP)

Measurement of Beam-beam Deflections at the Interaction Points of LEP

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Abstract

A precise method to tune the overlap of the counter-rotating beams at the interaction points is important to achieve good performances at LEP. The beam-beam deflection of the colliding beams has been measured for the first time at LEP in the vertical plane using beam position monitors located close to the interaction points. The dependence of the beam-beam deflection on the collision impact parameter has been used to optimize the setting of the electrostatic separators for best overlap in the vertical plane. The beam sizes at the interaction points have also been extracted from fits to the data.

Geneva, Switzerland

8 January 1996

1 Introduction

To obtain high luminosities and beam-beam tune shifts collisions with impact parameters that are small compared to the beam sizes have to be established at the interaction points (IP). For flat beams this is particularly delicate to achieve in the vertical plane where the beam sizes are small. At LEP the overlap of the beams in the vertical plane is adjusted with so-called "vernier" scans. During such a scan, the vertical separation of the beams is varied in steps with a local electrostatic bump. For each setting of the bump the luminosity is recorded. The separator setting corresponding to centered beams where the impact parameter is zero can be inferred from the highest luminosity point or from a fit to the luminosity curve. The separator bump amplitude that has to be applied at LEP is in the range of ± 20 μm at the interaction point. This is quite large in comparison to the typical vertical beam sizes of 3 to 6 μm. For beam energies of 45 GeV it takes about 5 to 10 minutes to perform a scan for one of the four IPs. The duration is dominated by the luminosity measurement time.

An alternative way to center the beams uses the deflections induced by the electromagnetic fields on the trajectories as the beams pass each other with a non-zero impact parameter. This technique requires accurate measurements of the beam angles and has been pioneered at the SLC [1, 2]. Successful attempts to measure the effect of the beam-beam interaction on the closed orbit have also been made at CESR [3] and at KEK [4]. An optimization of the beam overlap using such a technique has been performed 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 at LEP 200 where the lower Bhabha cross-section and the higher backgrounds in the luminosity detectors will require much longer integration times than at 45 GeV to obtain similar accuracies on the luminosity measurements.

I will describe in this note the method used at LEP to measure the beam-beam deflection and show results of the measurements made so far during the LEP high energy run.

2 The Beam-beam Interaction

We will consider only the case of flat beams and we will suppose that at the IP the vertical RMS beam size σ_y is smaller than the horizontal RMS beam size σ_x. We assume that the transverse and longitudinal charge distributions of the beams are Gaussian, that the RMS bunch length is much larger than σ_y and σ_x and that the transverse beam sizes do not change appreciably with the impact parameters. As two bunches pass each other at the IP, 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 [5, 6, 7, 8] :

$$\Delta x' = A\,\Im m F(x,y,\sigma_x,\sigma_y) \qquad\qquad \Delta y' = A\,\Re e F(x,y,\sigma_x,\sigma_y) \tag{1}$$

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

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

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

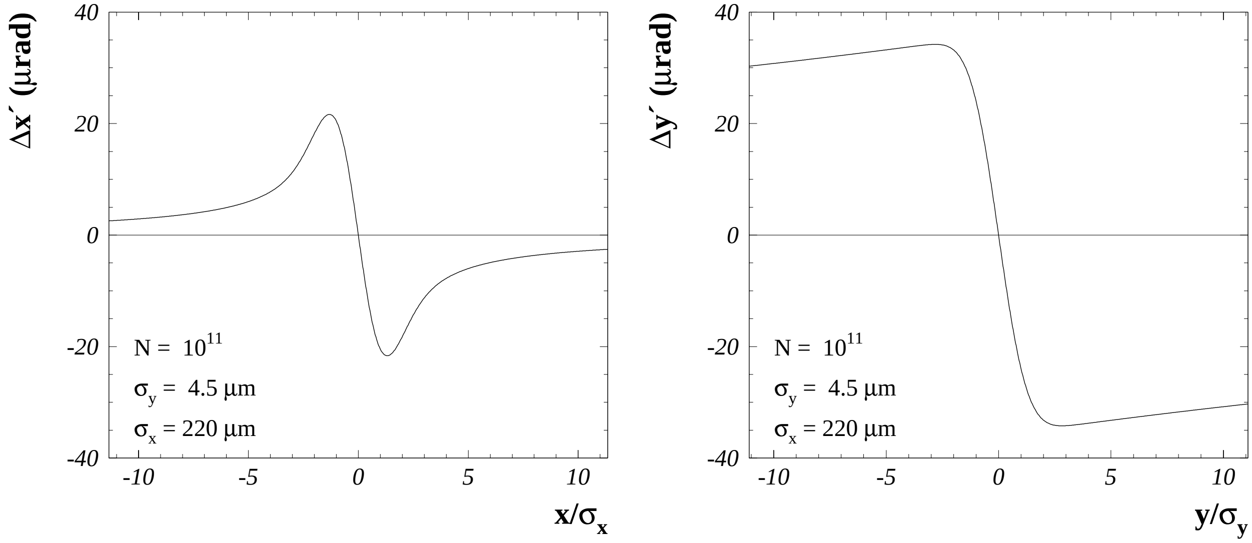

Figure 1: Beam-beam deflection angles of a single particle as a function of the horizontal (left) and the vertical distance (right) to the center of the counter-rotating bunch, given in units of RMS beam sizes. In both cases the particle is centered in the other transverse dimension. The beam energy is 45.6 GeV.

N is the number of particle in the bunch, x and y are the horizontal and vertical distances from the test particle to the center of the counter-rotating bunch. r_e is the classical electron radius (2.81810^{-15} m) and γ is the Lorentz factor. $w(z)$ is the complex error function :

$$w(z) = e^{-z^2}\left(1 - \frac{2}{\sqrt{\pi}} \int_0^{-iz} e^{-t^2}\, dt\right) \tag{4}$$

Figure 1 shows the deflection of a test particle for an example of LEP beam parameters at a beam energy of 45.6 GeV. The deflections vanish when the particle is centered. When the particle is close to the center of the other bunch, the beam-beam kick increases linearly with the separation :

$$\Delta x' = -\frac{4\pi\xi_x}{\beta_x^*}\, x \qquad\qquad \Delta y' = -\frac{4\pi\xi_y}{\beta_y^*}\, y \tag{5}$$

$\beta^*_{x(y)}$ are the betatron functions at the IP. The horizontal and vertical beam-beam tune shift parameters ξ_x and ξ_y are given by

$$\xi_x = \frac{r_e N \beta_x^*}{2\pi\gamma\sigma_x(\sigma_x + \sigma_y)} \qquad\qquad \xi_y = \frac{r_e N \beta_y^*}{2\pi\gamma\sigma_y(\sigma_x + \sigma_y)} \tag{6}$$

In the vertical plane $\Delta y'$ falls off very slowly for large y/σ_y because of the elliptical symmetry of the electromagnetic fields (since $\sigma_x \gg \sigma_y$). The largest absolute values of $\Delta y'$ are reached for $|y/\sigma_y| \approx 2.5$ and can be approximated by

$$\Delta y'_{max} \approx \frac{\sqrt{2\pi} N r_e}{\gamma \sigma_x} \tag{7}$$

when $\sigma_x \gg \sigma_y$. $\Delta y'_{max}$ depends essentially on the bunch population and on σ_x. The change of $\Delta y'$ with the horizontal separation x is shown in Figure 2. When $x/\sigma_x \leq 1$ the dependence is

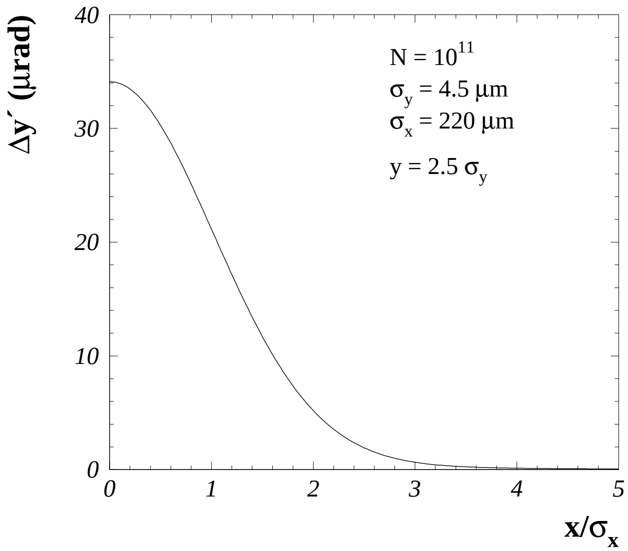

Figure 2: Dependence of the vertical beam-beam kick $\Delta y'$ of a single particle on the horizontal distance to the counter-rotating bunch. The vertical separation to the opposing bunch is set to $y = 2.5\sigma_y$ where $\Delta y'$ reaches its maximum. The beam energy is 45.6 GeV.

simply given by an exponential :

$$\Delta y'(x) \simeq e^{-x^2/2\sigma_x^2}\,\Delta y'(x=0) \tag{8}$$

The average kick seen by the whole bunch differs from the kick seen by a single particle [7, 8]. In the case of rigid bunches (the beam sizes do not change with the impact distance) the kick received by the whole bunch is obtained from Equation 1 by replacing the beam sizes σ_u $(u = x, y)$ with the effective sizes $\tilde{\sigma}_u$:

$$\tilde{\sigma}_u = \sqrt{(\sigma_u^+)^2 + (\sigma_u^-)^2} \tag{9}$$

where $+(-)$ labels the positron(electron) beam. When both beams have the same size $\tilde{\sigma}_u = \sqrt{2}\sigma_u$. The separations x and y represent in this case the distances between the centers of the two colliding bunches. When the beams are centered in either plane ($x = 0$ or $y = 0$) the corresponding deflection angle is zero. Steering the beams to produce no deflection will therefore maximize luminosity.

3 Principle of the Beam-beam Deflection Measurements

The coordinates of the beams at the IPs can be obtained from the LEP Beam Orbit Measurement system. The beam position is measured with two beam position monitors (BPM) on either side of the IP and extrapolated to the IP with the optical transfer matrices. The settings of electrostatic separators and of orbit corrector magnets are also taken into account. The vertical position of the collision point can be measured to an accuracy of 6 μm when this interpolation is combined with a measurement of the position of the low-beta quadrupoles [9]. A short term accuracy of about 1 μm can be achieved on the separation between the colliding beams. The beam angles can be measured with accuracies of the order of a few μrads.

The sensitivity to the beam-beam interaction can be enhanced if we take advantage of the fact that the beam-beam kicks are of opposite sign for the two beams. For this reason we define θ_{bb} as the difference of the deflections of the positron and electron beam :

$$\theta_{bb} = (\theta_L^+ - \theta_R^+) - (\theta_L^- - \theta_R^-) \tag{10}$$

where 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} involves only difference measurements and is therefore less sensitive to systematics errors of the BPMs.

Four vertical electrostatic separators can be used to vary the impact parameter of the collisions with a local orbit bump around a selected IP [10]. The expected change of θ_{bb} can be parameterized by a function $\mathcal{G}$ of the separation bump amplitude Δy using the expressions given in the previous chapter :

$$\mathcal{G}(\Delta y) = (A^{+} + A^{-})\, \Re e F(x = 0, \Delta y - \Delta y_{opt}, \sqrt{2}\sigma_x, \sqrt{2}\sigma_y) \; + \; \theta_0 \tag{11}$$

We assume here that the beams are centered in the horizontal plane ($x = 0$). Δy_{opt} gives the separator bump amplitude for which the beams are centered in the vertical plane. θ_0 is a free parameter that takes into account measurement systematics of the BPMs. $A^{+(-)}$ is given by :

$$A^{+(-)} = -\frac{\sqrt{\pi} N^{+(-)} r_e}{\gamma \sqrt{\sigma_x^2 - \sigma_y^2}} \tag{12}$$

$N^{+(-)}$ is the average number of particles in the position(electron) bunch. The measured deflections θ_{bb} are fitted with the MINUIT [11] program to the function $\mathcal{G}$ of Equation 11 using four free parameters :

$$\theta_0, \qquad \Delta y_{opt}, \qquad \sigma_x, \qquad \sigma_y \tag{13}$$

The average numbers of particles $N^{+(-)}$ are fixed and obtained from the bunch currents. The beam sizes correspond to ($u = x, y$) :

$$\sigma_u = \frac{\tilde{\sigma}_u}{\sqrt{2}} \tag{14}$$

where $\tilde{\sigma}_u$ has been defined with Equation 9.

4 Results of Beam-beam Deflection Scans

During the LEP high energy run in 1995 a few scans of the beam-beam deflection angle were performed in physics or in end-of-fill experiments. The local electrostatic separator bumps were varied manually 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 the pickups PU.QS0 and PU.QS4 on the left and right side of the IP [12]. The resulting data sample was fitted to the function $\mathcal{G}$. The scatter of the data around the fitted function shows that the accuracies on θ_{bb} are in the range of 1 to 5 μrad. Fits of the e^+e^- difference orbit (performed with the method described in [13]) show that the horizontal separation between the beams was on average smaller than 10 μm. The assumption used in Equation 11 that the beams are centered in the horizontal plane is therefore a good approximation since $\sigma_x \geq 200$ μm. Two examples of scans are shown in Figures 3 and 4. The scan in IP2 was performed with low bunch currents at the end of a fill. The separation was varied by about 110 μm to test the beam-beam kick parameterization 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 4.

Table 1 shows a summary of all measurements that have been performed. During a large fraction of the high energy run, LEP was operated with the Bunch Train separation bump amplitudes set to 20% of their nominal values [10]. In such a configuration the voltages on the electrostatic separators do not allow large amplitude scans in IPs 4 and 8. For this reason all

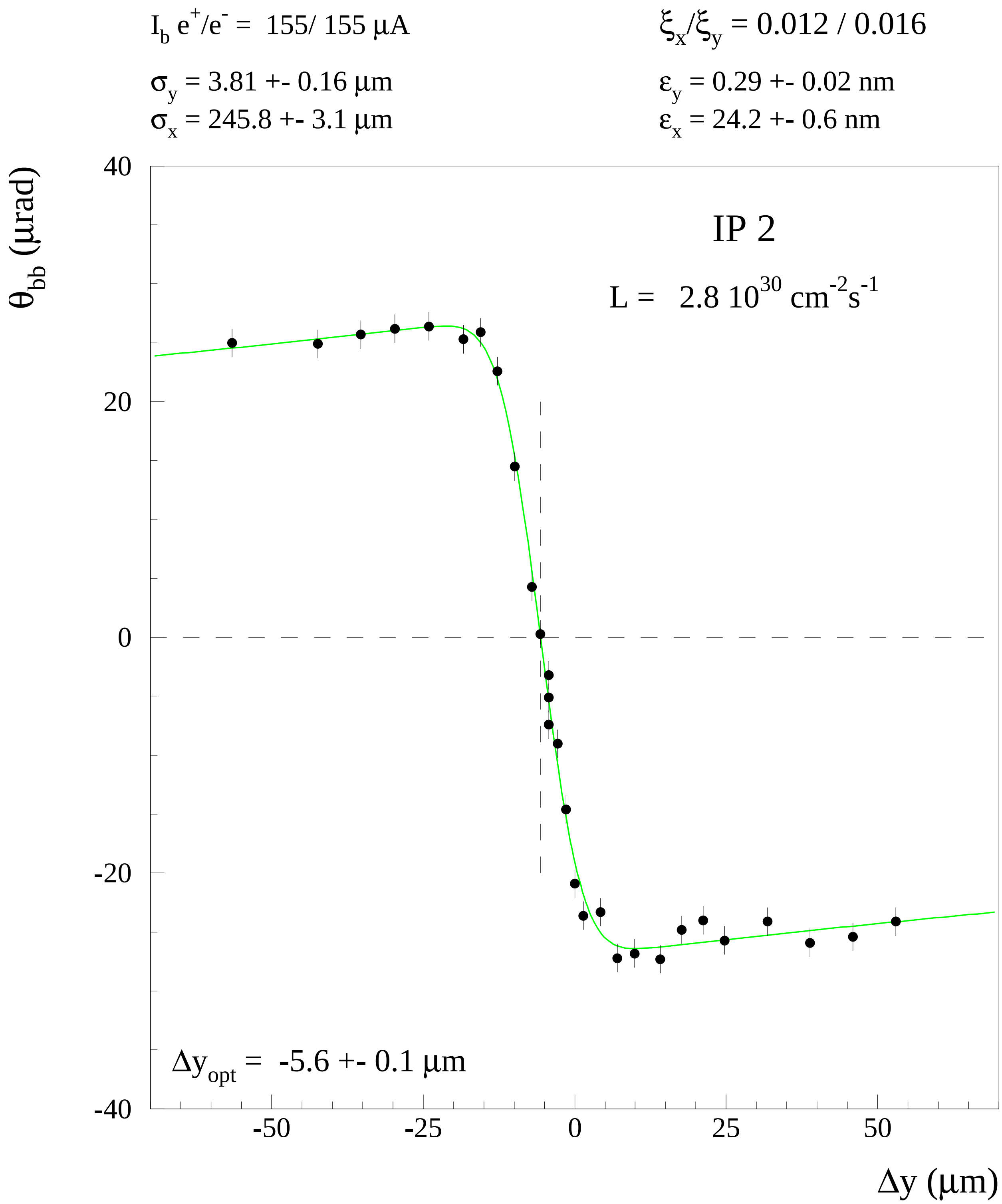

Figure 3: Beam-beam deflection scan in IP2 at 65.1 GeV. θ_{bb} is shown as a function of the separation bump amplitude Δy. The systematic offset θ_0 is already subtracted from the data. The solid line is the fitted function. The emittances ε_x and ε_y, the luminosity L and the beam-beam tune shifts ξ_x and ξ_y have been calculated from the fitted beam sizes and the bunch currents. Δy_{opt} is the optimum separator position.

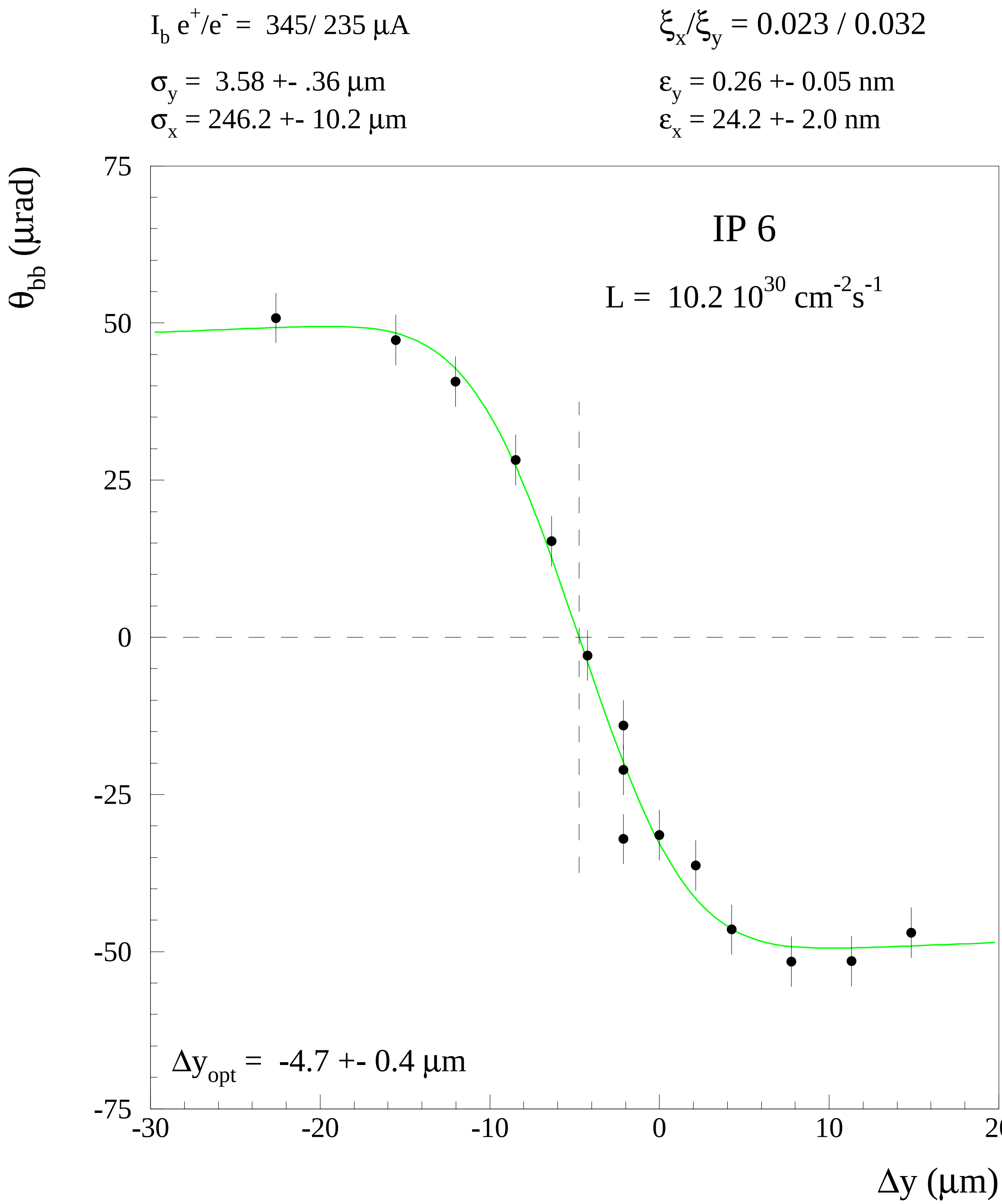

Figure 4: Beam-beam deflection scan in IP6 at 65.1 GeV. θ_{bb} is shown as a function of the separation bump amplitude Δy. The systematic offset θ_0 is already subtracted from the data. The solid line is the fitted function. The emittances ε_x and ε_y, the luminosity L and the beam-beam tune shifts ξ_x and ξ_y have been calculated from the fitted beam sizes and the bunch currents. Δy_{opt} is the optimum separator position.

Table 1: Summary of the beam-beam scans performed during the high energy run of LEP. For each scan the fitted optimum separator setting is given together with the beam sizes at the IP and the systematic offset θ_0. $I^{+(-)}$ is the average $e^{+(-)}$ bunch current.

Fill	IP	E_{beam} (GeV)	I^+ (μA)	I^- (μA)	θ_0 (μrad)	Δy_{opt} (μm)	σ_y (μm)	σ_x (μm)
3108	2	65.1	155	155	-20.7 $\pm$ 0.3	-5.6 $\pm$ 0.2	3.8 $\pm$ 0.2	246 $\pm$ 3
3126	2	65.1	270	240	-50.6 $\pm$ 1.0	-5.1 $\pm$ 0.2	3.8 $\pm$ 0.3	239 $\pm$ 7
3105	6	65.1	145	130	-54.7 $\pm$ 0.4	-15.7 $\pm$ 0.3	4.3 $\pm$ 0.3	220 $\pm$ 5
3109	6	65.1	345	235	-72.1 $\pm$ 1.7	-4.7 $\pm$ 0.4	3.6 $\pm$ 0.4	246 $\pm$ 10
3159	6	68.1	265	245	-69.1 $\pm$ 1.7	-6.1 $\pm$ 0.3	3.6 $\pm$ 0.4	209 $\pm$ 10
3183	6	68.1	360	280	-60.6 $\pm$ 1.9	-3.6 $\pm$ 0.4	3.4 $\pm$ 0.5	279 $\pm$ 16

scans were made in IPs 2 and 6. For each scan it has been checked that the settings found for Δy_{opt} corresponds to the point of highest luminosity within about ± 1 μm. In one case (fill 3183) a "vernier" scan of the luminosity performed just after the experiment gave the same optimum within the errors of the fits. The large scatter of Δy_{opt} for IP6 is partially due to changes in the amplitude of the Bunch Train separation bumps. But it also reflects some strange instability of the luminosity observed during the high energy run for IP6. More comparative studies between beam-beam deflection and standard "vernier" luminosity scans are clearly necessary to evaluate the systematic errors on Δy_{opt}.

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

$$L = \frac{kN^+N^-f}{4\pi\sigma_x\sigma_y} \tag{15}$$

$k(=4)$ is the number of bunches per beam and f is the revolution frequency. Table 2 shows that in all cases 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 Δy_{opt}. The fits do not seem to be perturbed very much by the changes in beam sizes that occur during the scan, particularly for separations in the range $1 \leq y/\sigma_y \leq 3$. These beam size measurements at the IP are an interesting side product of the scans. They show that for beam energies of 65.1 and 68.1 GeV, the vertical beam emittances were in the

Table 2: This table shows the vertical and horizontal emittances ε_y and ε_x calculated from the fitted beam sizes using nominal betatron functions ($\beta_x^* = 2.5$ m, $\beta_y^* = 5$ cm) and assuming that there is no dispersion at the IP. In the last two columns the luminosity L_{fit} obtained from Equation 15 is compared to the luminosity L_{exp} measured by the corresponding LEP experiment.

Fill	IP	E_{beam} (GeV)	ε_y (nm)	ε_x (nm)	L_{fit} ($10^{30} cm^{-2}s^{-1}$)	L_{exp} ($10^{30} cm^{-2}s^{-1}$)
3108	2	65.1	0.29 $\pm$ 0.02	24.2 $\pm$ 0.6	2.8 $\pm$ 0.2	3.3 $\pm$ 0.3
3126	2	65.1	0.28 $\pm$ 0.04	22.8 $\pm$ 1.4	8.0 $\pm$ 0.6	9.5 $\pm$ 0.5
3105	6	65.1	0.37 $\pm$ 0.04	19.3 $\pm$ 0.8	2.2 $\pm$ 0.2	---
3109	6	65.1	0.26 $\pm$ 0.05	24.2 $\pm$ 2.0	10.2 $\pm$ 1.1	11.0 $\pm$ 1.0
3159	6	68.1	0.26 $\pm$ 0.05	17.5 $\pm$ 1.5	9.6 $\pm$ 1.1	9.5 $\pm$ 0.5
3183	6	68.1	0.23 $\pm$ 0.06	31.1 $\pm$ 3.5	11.7 $\pm$ 1.7	10.5 $\pm$ 0.5

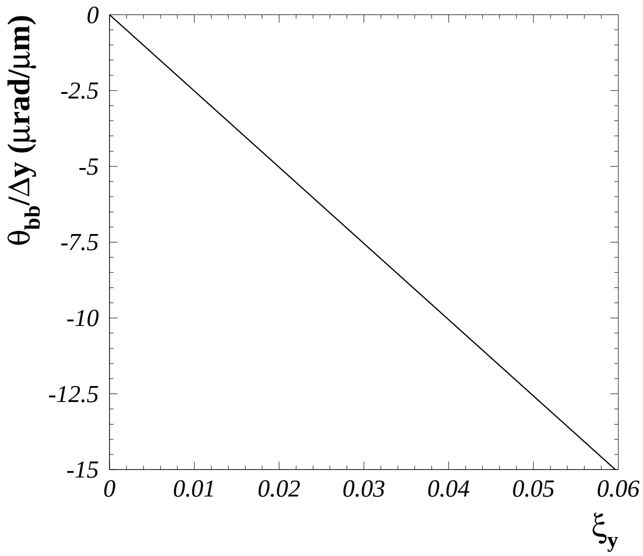

Figure 5: Sensitivity of the beam-beam deflection angle θ_{bb} to the collision impact parameter Δy as a function of the vertical beam-beam tune shift for $\beta_y^* = 5$ cm when the beams are almost centered.

range 0.2 to 0.3 nm. The natural horizontal emittances on the central orbit calculated with MAD [14] for 65.1 and 68.1 GeV are 24.4 and 26.7 nm. In general the measured ε_x agree quite well with the prediction. They confirm observations that the beams did not blow up very much horizontally when they were brought into collision at these energies. The horizontal emittance measured for fill 3159 is extremely low, although the predicted luminosity is correct. This difference cannot be explained with a change of the central orbit or with dispersion at the IP. Betatron function beating in the vertical plane due to the low-beta quadrupoles might lead to a wrong interpolation and to an over-estimate of θ_{bb}. The fit would then give an overestimate of σ_x (Equation 7), but this hypothesis could not be checked. The beam size measurements would clearly profit from systematic studies where the emittance is deliberately varied using the damping partition number (by a RF frequency change) or the emittance wigglers.

The spread of the systematic offsets θ_0 in Table 1 gives an idea of the long term stability of the BPM measurements and interpolations. The largest differences in θ_0 for a given IP are in fact due to the gain change of the BPM electronics around 220 μA per bunch. When the impact parameter of the collisions is close to zero, the sensitivity of θ_{bb} to the distance between the two colliding bunches is proportional to ξ_y :

$$\frac{\theta_{bb}}{\Delta y} = -\frac{4\pi\xi_y}{\beta_y^*} \tag{16}$$

The sensitivity is shown as a function of ξ_y in Figure 4. To be able to operate a feedback on θ_{bb} and to adjust Δy_{opt} during fills or from fill to fill with an accuracy better than 0.5 μm, θ_0 must be stable to about $\pm$ 5 μrad for $\xi_y \approx 0.04$. The results for θ_0 show that such an accuracy has not been achieved yet. More work is required at this level before a feedback can be operated on the basis of the beam-beam deflection measurements.

5 Conclusions and Outlook

Scans of the vertical beam-beam deflections have been performed successfully at LEP. Thanks to the very good performance of the BPMs, they provide measurements of the collision impact parameter with an accuracy below 1 μm at the IP. Luminosities predicted with beam sizes extracted from the fits agreed well with direct measurements by the experiments. Some studies, particularly comparisons with luminosity "vernier" scans, will be helpful to understand the systematic errors and the limitations of the beam-beam deflection scans.

In the future it will be possible to increase the speed of the scans using an automatic procedure. The measurements for one separator setting could be reduced to about 15 seconds provided a special readout of the few pickups of interest for the scans can be implemented [15]. A complete scan will require about 12 points in the range of $\pm 4\sigma_y$. The duration of such a scan would then be 3 minutes. This would make these scans very useful optimization tools at LEP 200.

A continuous monitoring of θ_{bb} would allow to stabilize the separation of the beams over longer time spans. From the results shown in this note, it is clear that more work is required to understand the stability of the measurements. Improvements at the level of the BPM gain systematics planned for 1996 could make such a feedback possible.

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