Evaluation of the emittances in LEP from the observed frequencies of the coherent beam-beam modes

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Abstract An automatic procedure has been installed in the LEP control system which determines the horizontal and vertical beam emittances from the frequencies of the coherent beam-beam modes. The procedure reads optical LEP parameters, bunch currents, beam energy, vertical beam separations, frequencies of the coherent beam-beam modes from the LEP instrumentation. The frequencies of the coherent modes, i.e. the eigenvalues of the coupled linear beam-beam equations, are computed from these data and the emittances. The emittances are varied by the procedure until the calculated and observed frequencies agree. The beam-beam strength parameters and the luminosities are by-products of this calculation.

1 Introduction

Coherent beam-beam oscillations are a good probe for the beam-beam interaction in storage rings [1]. They can be excited and their tunes, i.e. the ratios between coherent oscillation frequencies and the revolution frequency, can be measured by the usual tune measurement system. The tunes are related to the horizontal and vertical emittances, the bunch populations, and luminosities. The earlier BBMODE program [2] calculates the tunes of the coherent beam-beam modes from the machine and beam parameters. We have now incorporated this program in a fitting program BBFIT which adjusts the machine and beam parameters such that the observed and computed tunes of the coherent beam-beam modes agree.

2 Bunch Motion

We treat the motion of the centres of gravity of the bunches in linear approximation, keeping only linear terms in the horizontal and vertical positions, $\bar{x}$ and $\bar{y}$, and horizontal and vertical slopes, $\bar{x}'$ and $\bar{y}'$, and using a matrix and eigenvalue technique. We take the deviations of the bunch density distribution from a Gaussian due to the beam-beam effect into account by applying correction factors. Our fitting algorithm uses a standard fitting routine to obtain the machine tunes and the horizontal and vertical emittances from the observed coherent beam-beam tunes.

Linear Formalism

Since in linear approximation, the horizontal and vertical motions are independent, we can treat them separately. In the equations below, we write $\bar{z}$ for either $\bar{x}$ or $\bar{y}$, and $\bar{z}'$ for either $\bar{x}'$ or $\bar{y}'$. There are four e^+ and four e^- bunches circulating in LEP. The motion of their centres of gravity can be described by 16×16 matrices operating on a column vector with 16 components, 8 positions and 8 slopes. A turn in LEP is described by a product of eight kick matrices alternating with eight arc matrices. The kick matrices describe the four bunch-bunch collisions which happen simultaneously. The arc matrices transport the bunches through the arcs from one interaction point to the next. The tunes of the coherent modes are the phases of the eigenvalues of the turn matrix. The details of the algebra are given in [2]. The lowest tune is close to the unperturbed fractional tune Q_z. Since the beam-beam force in e^+e^- colliders is attractive, the tune shifts of the coherent beam-beam modes are positive, and the highest tune is about $4F_z(r)\xi_z$ higher than Q_z; $F_z(r)$ is given in Equ.(3).

Meller-Siemann-Yokoya Factors

The kick $z'_\pm$ which a single test particle in the $e^\pm$ beam receives when crossing a bunch in the $e^\mp$ beam is given by:

$$z'_\pm = \frac{2r_e N^\mp (z_\pm - \bar{z}_\mp)}{\gamma^\pm \sigma_z^\mp (\sigma_x^\mp + \sigma_y^\mp)} \qquad (1)$$

Here, r_e is the classical electron radius, $N^\mp$ is the population of the opposite $e^\mp$ bunch, $z_\pm$ is the displacement of the test particle, $\bar{z}_\mp$ is the barycentre displacement of the bunch in the z direction at the IP, $\gamma^\pm$ is the Lorentz factor, and $\sigma_z^\mp$ is the rms beam radius of the $e^\mp$ bunch in the z direction. The average kick $\bar{z}'_\pm$ which a Gaussian bunch in the $e^\pm$ beam receives when crossing the opposite bunch with displacement $(\bar{z}_\pm - \bar{z}_\mp)$ is given by an expression which has the same form as Equ. 1, but with the mean square beam radii $(\sigma_z^\mp)^2$ replaced by $\Sigma_z^2 = (\sigma_z^\pm)^2 + (\sigma_z^\mp)^2$ [3]. When the rms bunch radii in the two beams are equal, the kick is exactly half the kick shown in Equ. (1). Yokoya et al. [4] give graphs how the bunch shape is distorted by the beam-beam collisions. The average kick $\bar{z}'_\pm$ received by such a bunch in the $e^\pm$ beam when crossing the opposite bunch in the $e^\mp$ beam with displacement $(\bar{z}_\pm - \bar{z}_\mp)$ is given by:

$$\bar{z}'_\pm = \frac{2F_z(r) r_e N^\mp (\bar{z}_\pm - \bar{z}_\mp)}{\gamma^\pm \Sigma_z (\Sigma_x + \Sigma_y)} \qquad (2)$$

The correction factors $F_z(r)$ were computed by Meller and Siemann [5] and Yokoya et al. [4]. A numerical fit to the results of the latter is:

$$F_x(r) = 1.330 - 0.370r + 0.279r^2 \quad \text{and} \quad F_y(r) = F_x(1-r) \qquad (3)$$

with $r = \sigma_y/(\sigma_x + \sigma_y)$. These correction factors are included in our calculation, by multiplying the appropriate elements of the kick matrices [2].

Fitting Algorithm

The fitting program BBFIT is written in Fortran. It reads the machine and beam parameters, and the lowest and highest observed coherent beam-beam tunes in the horizontal plane $\check{q}_x$ and $\hat{q}_x$, and in the vertical plane $\check{q}_y$ and $\hat{q}_y$. It then invokes the NAGLIB fitting routine C05NBF [6]. This routine solves a system of N nonlinear equations in N variables. It chooses the correction at each step as a convex combination of the Newton and scaled gradient directions. It varies the horizontal and vertical

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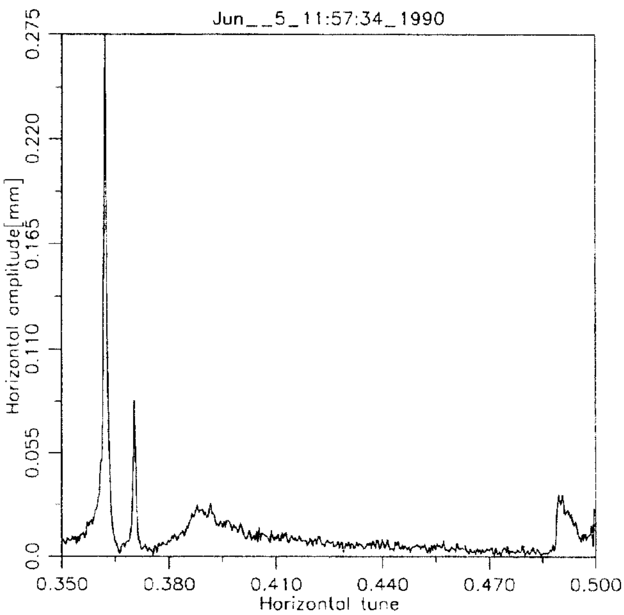

Figure 1: Horizontal spectrum

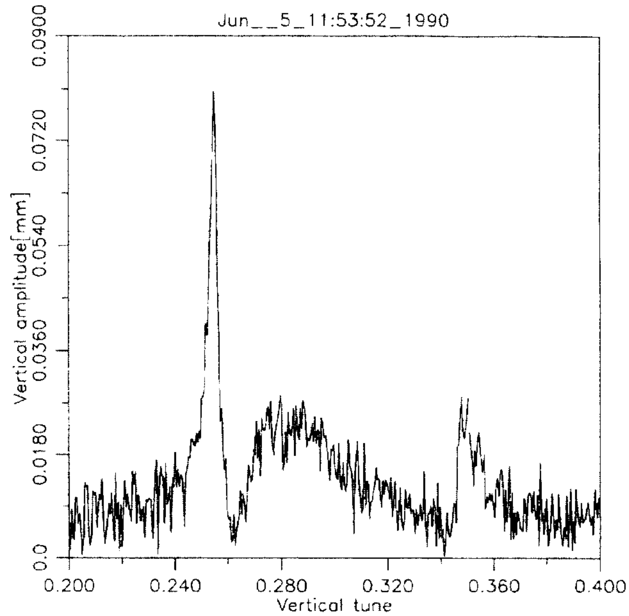

Figure 2: Vertical spectrum

tunes Q_x and Q_y, and the horizontal and vertical emittances E_x and E_y, until the fitted coherent tunes agree with the observed values $\check{q}_x$, $\hat{q}_x$, $\check{q}_y$ and $\hat{q}_y$. It returns the eight coherent horizontal and vertical tunes q_{xi} and q_{yi}, the horizontal and vertical emittances E_x and E_y, the horizontal and vertical tunes Q_x and Q_y, the luminosities in all eight IP's L_i, the beam-beam strength parameters in the horizontal and vertical planes, ξ_y and ξ_x.

3 Implementation in the Control System

The upper level of the LEP control system is composed of operator consoles, servers, and process computers which run under the Unix operating system and are connected in a network [7]. The procedure has been installed in two parts:

- A C program runs on an operator console, handles the dialog with the operator, reads the machine and beam parameters, writes an ASCII data file for the fitting program BBFIT, and launches it.
- The fitting program BBFIT runs in a server, reads the ASCII data prepared for it, executes the fitting algorithm, and writes the results into another ASCII file.

All ASCII files are given names which contain the calendar date and the time of the day.

Data Collection

The machine and beam parameters are collected by the C program. The optical parameters are stored in the LEP control system using the Table File System TFS [8] in the reference dataset directory. A special file, the Run Table [9], contains the name of the TFS file with the Twiss parameters of the configuration which is currently used in LEP. The C program gets this name from the Run Table and reads from the Twiss file the values of the amplitude functions β_x and β_y at, and the phase advances μ_x and μ_y between the eight interaction points IP in LEP.

The intensities of all four e^+ and all four e^- bunches are regularly read by a dc current transformer [10]. A synchronous analog signal processor tracks the bunches over many turns. The readings are stored on a process computer as a TFS table which in turn is read by the C program.

The beam energy is obtained from the magnetic field in the reference dipole in series with the LEP dipole chain [11]. The measurement is initiated by a process computer which is driven in turn by a remote procedure call from the C program.

The e^+ and e^- beams are vertically separated at the odd interaction points by electrostatic separators [12]. The C program reads the TFS table containing the vertical distances between the two beams at all interaction points which is stored in the current dataset directory of a dedicated process computer.

Tune Measurement

The tunes of the coherent beam-beam modes were measured with the LEP Q-monitoring system [13], using the swept frequency mode. Horizontal or vertical oscillations of one of the eight bunches in LEP are driven by a horizontal or vertical kicker magnet whose field varies like a sine wave. The frequency is varied over a prescribed range, typically about half a unit in tune, in a few hundred steps. The response of one of the eight LEP bunches to that excitation is recorded. The horizontal tune spectrum obtained is shown in Fig. 1, and the vertical tune spectrum in Fig. 2. In the vertical spectrum, a single peak is observed in the neighbourhood of the unperturbed tune. In the horizontal spectrum, a double peak is observed there. In both planes, a weaker signal is observed at a higher tune. We have identified the lower one of

No.	1	2	3	4
e^-	259.7	331.5	270.6	269.6
e^+	207.0	249.8	260.7	227.5

Table 1: Bunch Currents in μA

Quant.	Hor.	Vert.
Q	0.3623	0.2545
E	32.0 nm	1.8 nm
$<\xi>$	0.0216	0.0178

Table 2: Fitting Results

the double peak with the lowest tune $\check{q}_x = 0.3623$, and the lowest vertical peak with $\check{q}_y = 0.2545$, and the upper edge of the weaker signal with the highest tunes $\hat{q}_x = 0.4899$ and $\hat{q}_y = 0.3487$.

4 Results

We tested the BBFIT procedure at a beam energy of 46.5 GeV in the LEP configuration N07C46 with $\beta_x = 1.75$ m and $\beta_y = 0.07$ m at the experimental IP's. The bunch currents are shown in Tab. 1. The fitted results are shown in Tab. 2. The fitted tunes Q_z agree with the lowest tunes $\check{q}_z$. This is to be expected since the differences in the bunch currents are small. The horizontal emittance E_x is close to the nominal figure 34.9 nm.

The computed luminosities are shown in Tab. 3. Since the same pairs of bunches collide in diametrically opposite IP's, the luminosities there must be the same, as long as the β_z values there are identical, as we assume.

The luminosity monitors were not running during the tests. Therefore, a direct comparison between the measured values and those obtained from fitting the tune data is not possible. However, the luminosities shown in Tab. 3 agree quite well with those expected at the bunch currents shown in Tab. 1.

The computed tunes of the coherent modes are displayed in Tab. 4. In both planes, there are two closely spaced tunes near the lowest and the highest tunes, and four closely spaced tunes in the middle. In a perfect LEP with equal e^+ and e^- bunch currents and large enough separations in the odd pits such that the beam-beam effect is negligible there, there are just three tunes because the lowest and highest tune appear twice, and the middle tune four times. When the e^+ and e^- bunch currents are different, but the separation in the odd pits is still large, there are four tunes, each appearing twice. The split between the two middle pairs is a measure of the current difference. If the separations in the odd pits are smaller, such that the beam-beam effect there is not negligible, the four pairs are all split, as shown in Tab. 4. As expected, the horizontal splits are larger than the vertical ones.

A flying wire scanner allows an independent observation of the horizontal and vertical emittance. Only the vertical scanner was operational at the time of the tests. The emittances obtained for all eight bunches are compiled in Tab. 5. The emittances of the electron bunches are consistent, and about a factor of two higher than those obtained from the coherent beam-beam tunes. The emittances of the positron bunches show a large fluctuation, and are a factor from 2.5 to 5 times larger than those obtained from the coherent beam-beam tunes.

Pits	$L/10^{30}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
2 & 6	2.75
4 & 8	2.72

Table 3: Luminosities

Hor.	0.4899	0.4815	0.4282	0.4205
	0.4139	0.4125	0.3652	0.3623
Vert.	0.3487	0.3432	0.3033	0.2974
	0.2925	0.2916	0.2547	0.2545

Table 4: Tunes of Coherent Modes

5 Conclusions

We have installed a fast and easy-to-use procedure for measuring emittances in the LEP control system. It is based on measuring the tunes of the coherent beam-beam modes. In real time, the fitting is very much faster than obtaining the coherent beam-beam tunes with the tune measuring system. We find emittances in good agreement with those obtained from luminosity monitors. The emittance ratio E_y/E_x is about 5.6%. Our method yields a smaller vertical emittance than the flying wire scanner. Simultaneous observations of the coherent beam-beam tunes and of the luminosities will provide a more accurate calibration of our fitting method, and in particular of the correction factors [4].

No.	1	2	3	4
e^-	4.491	4.440	4.704	4.431
e^+	7.523	5.835	8.719	9.506

Table 5: Vertical Emittances [nm] from Flying Wire Data

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