Measurement of the beam-beam effects as a function of the separation in LEP

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1 Abstract

In the experiments presented here the tune shift generated by the beam-beam effect was measured as function of a vertical separation between the positron and electron bunches in LEP. The experiments were performed at the injection energy of LEP (20 GeV). The results are compared with calculations of the tune shift for separated non-round beams. In the present LEP operation the tune shift due to the beam-beam force for fully separated beams is negligable. This will change with a luminosity upgrade of LEP which will be achieved by both increasing the intensity per bunch and the number of bunches. Under these conditions the total tune shift, coming from the interaction points where the beams are separated, will become important and this study could help to better understand the limitations due to beam-beam effects.

2 Introduction

One of the most important parameters limiting the bunch intensities, and hence the luminosity in electron-positron colliders is the beam-beam interaction.The colliding electron and positron bunches act on each other as non linear lenses.The strength of such a nonlinear lens depends on the intensity of the beams. The beam-beam interaction introduces a tune shift which is depending on the betatron occillation amplitude of the individual particles. This results in a tune spread which might exceed dangerous resonances. Moreover, due to the nonlinearity of the beam-beam interaction higher order resonances are created. The consequence of these two effects is a transverse blow up of the beams if the beam intensity and therefore the tune spread are above a certain critical value. The emittance blow up can lead to a reduced lifetime.
The strength of the beam-beam interaction is usually expressed as a function of the so-called linear tune shift, i.e. the tune shift due to the beam-beam force on a particle with zero betatron oscillation amplitude. This tune shift depends on the intensity and the transverse dimensions (the density) of the other beam and it inversely proportional to the energy. At LEP we observe, that the beam-beam limit at 46 GeV is substatially higher as at 20 GeV, which is probably related to the different values for the damping decrement.
One way of reducing the beam-beam interaction is the separation of the beams in the unwanted collision points. In LEP it is possible to separate the beams by local bumps using electrostatic deflectors around the eight collision points [1]. Separating the beams in the vertical plane reduces the linear tune shift in both planes so that higher beam currents can be accumulated. However it is not clear that the beam-beam limit will still be the same as in the unseparated case. For head-on collisions only even higher order resonances are created whereas in the separated crossings also odd resonances come up.
In this paper we report on some experiments that were done at LEP in order to study the beam-beam interaction as a function of vertical separation. We first measured the linear tune shift as a function of separation in both the strong-weak and strong-strong regime and compared this data with theoretical calculation for non round Gaussian beams. We also measured the beam blow up and the intensity lifetimes in order to find the beam-beam limit when the separation is reduced.

3 Experimental procedure

Three experiments on the beam-beam tune shift were performed at 20 GeV with only one electron bunch colliding with one positron bunch in two low beta insertions. The vertical separation in both points can be varied in a range from 0 to 1.8 mm which corresponds roughly to a separation of 20 times the beam size. In order to measure the linear tune shift two approaches were adopted. The most accurate method is to measure the tune shift in the strong-weak regime. The intensity of the weak beam is low in order to avoid any influence on the strong beam. In this case the tune of the weak beam is identical to the single particle tune. The tune was measured by exciting on bunch with white noise and measuring its frequency response. Another way to measure the tune shift is with two bunches of the same high intensity. The tune measurement in this regime revails two peaks in the frequency spectrum coming from two coherent beam-beam modes, the so called π and σ modes. The difference between these two modes δQ is proportional to the linear beam-beam tune shift :

$$\delta Q = \alpha \times \xi$$

Different values for α are quoted in the literature ranging from 1 to 1.34 ([2], [3], [4] and [5]). Three different measurements were done. In the first experiment the intensity of the strong bunch was chosen low enough (positrons 25 μA) so that the weak bunch (electrons 12 μA) could survive with zero separation. The working point was .37 QH and .27 QV. The beam size at the interaction point of the strong bunch was 0.57 mm horizontally and 0.098 mm vertically (1 σ).
In the second experiment the current of the strong bunch was 280 μA and of the weak one 40 μA. The beam size of the strong bunch at the interaction point was 0.091 mm in the vertical plane and 0.88 mm in the horizontal plane. The separation between the beams was reduced until the weak beam was lost. Both horizontal and vertical beam size of the weak beam was measured using a wire scanner.
The third experiment was done with equally strong beams of 280 μA each. The separation was reduced until one of the two beams was lost.

4 Results

The measured vertical and horizontal tune shifts from the first experiment are plotted in Fig.1. The tune measurements for the second and the third experiment are plotted in Fig.2.

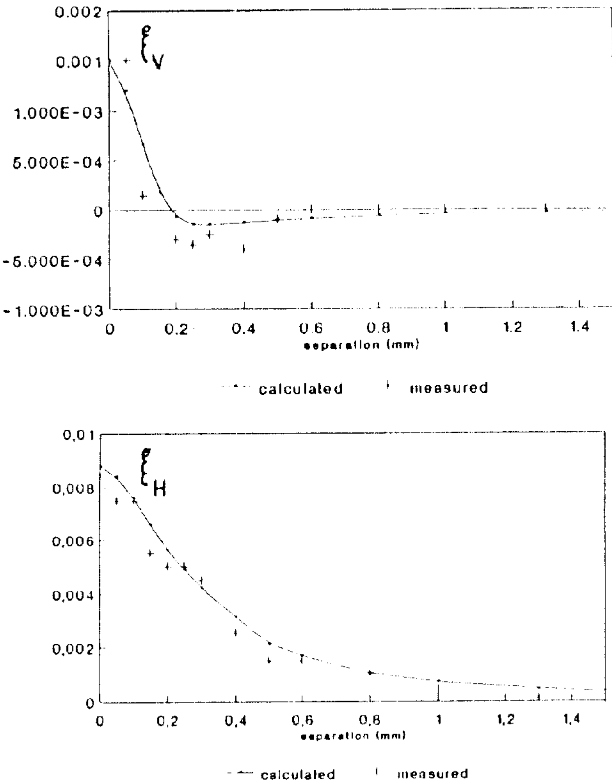

Fig.1: Measured and calculated tune shifts as a funtion of vertical separation. $\sigma_x = .57mm$, $\sigma_y = .098mm$ for the strong beam.

The theoretical curves in these figures were obtained from an analytical calculation of the detuning function using the Hamiltonian formalism [6].
This calculation was done for round and non-round beams which are separated in the vertical or in the horizontal plane. As we introduce a separation between the beams in one plane, the detuning function changes. The equation of the equivalent potential created by the bunch and seen by a counterrotating particle is different for separated and non-separated beams. For a vertical separation between the beams one finds :

$$V(x, y - y_0) \quad = \quad -\frac{Nr}{\gamma} \times \int_0^\infty \frac{1 - \exp -\left(\frac{x^2}{2\sigma_x^2 + t} + \frac{(y - y_0)^2}{2\sigma_y^2 + t}\right)}{\sqrt{(2\sigma_x^2 + t)(2\sigma_y^2 + t)}} \times dt \qquad (1)$$

where:

t : integration's constant
σ : standard deviation of the beam with gaussian distribution in x,y plane
N : total number of particles in a bunch
y_0: deviation of one beam with respect to the other
r: classical radius of the particle
γ : the relativistic factor

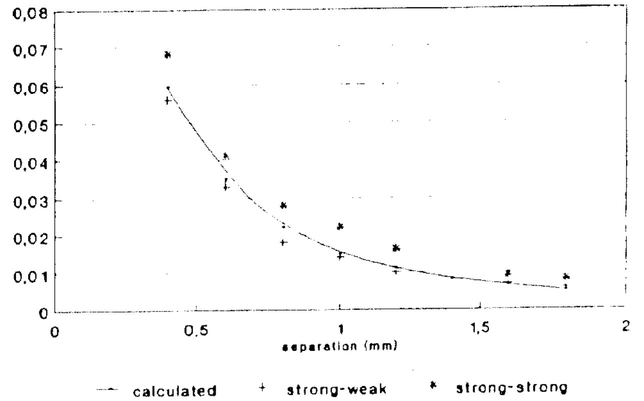

Fig.2: Horizontal tune shifts in strong-weak and strong-strong cases.

The derivative of the equivalent potential yields the kick and after some arithmetics, the equation of the detuning function. We obtain different equations for the detuning function depending on the aspect ratio of the strong beam ($f' = \frac{\sigma_x}{\sigma_y}$) [6]. These equations are solved with a help of a computer program and the detuning function is plotted as a function of the particle amplitude for several values of the separation. The detuning function is normalised to ξ the linear beam-beam tune shift. At zero particle amplitude the detuning function is identical to the linear beam-beam tune shift.

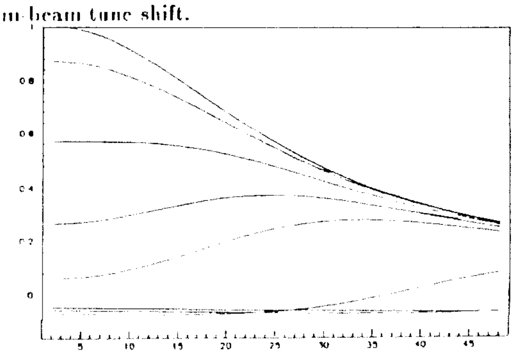

Fig.3: Detuning function in the vertical plane as a function of the particle amplitudes for different values of the separation.

As can be seen from Fig.1 and Fig.2 the calculation reproduces very well the measurements in the strong-weak regime. The tune split between the π and σ mode in the strong-strong case is systematically higher than the measured and calculated tune shift (Fig.2). The ratio is varying from 1.2 to 1.6 (Fig.4)

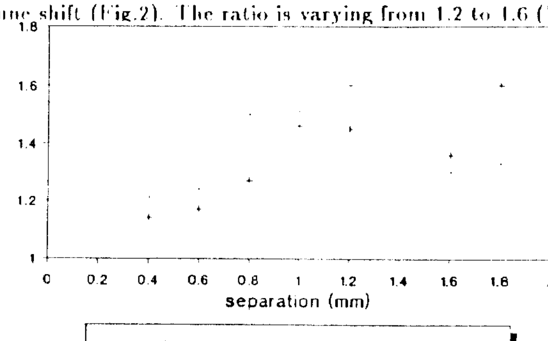

Fig.4: Ratio between $\Delta(\pi - \sigma)$ and the linear tune shift.

In the second and the third experiment the beams were lost when the separation was reduced to 0.4 mm, corresponding to a total tune shift of 0.06 (the total tune shift is the sum of the tune shifts for all interaction points). From previous experiments.we know that for head-on collisions at the same working point a tune shift of 0.08 can be achieved indicating that the beam-beam limit is lower for beams which are separated by a small amount.

A forth experiment was done with LEP operating at a beam energy of 46 GeV. If the beams are separated, the symmetry is broken and additional resonances of odd order are excited. It comes therefore not as a surprise, that in the case of separated beams the blow-up by the beam-beam effect is stronger than without any separation. The luminosity and the vertical beam size was recorded during a scan were the separation between the two beams was changed at all interaction points between -45 μm and 45 μm(see Fig.5). The currents of the beams were

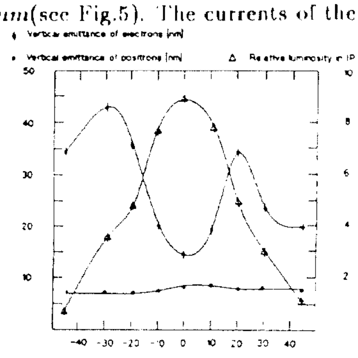

Fig.5: Vertical emittance of the electron and positron beam as a function of the beam separation at 45 GeV. The relative luminosity, measured in interaction region 4 is plotted as well.

0.12 mA/bunch for the electrons and 0.16 mA/bunch for the positrons. For zero separation the emittances of the two beams were already slightly different. With small separation the emittance of the weaker beam increased significantly, whereas the emittance of the stronger beam remained constant. For larger values of the separation the blow up decreased again.

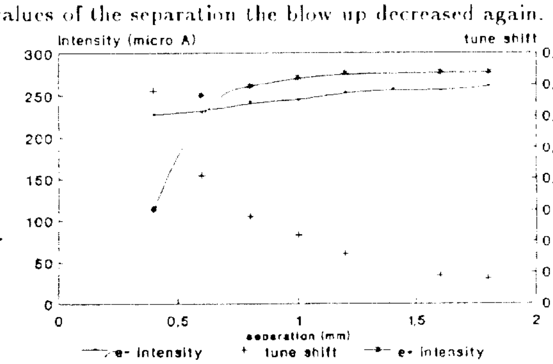

Fig.6: Intensities of the electron and positron bunch during a separation scan.

Another interesting observation was done at injection energy (20 GeV) : Usually the weaker beam is blown up and lost first. That this is not always true for LEP can be seen in Fig.6 : the beam with the higher intensity disappears first. This is due to a particularity in the RF system of LEP which is modulated in amplitude. If the phase of this modulated wave is not exactly optimised, the synchrotron tune of the electron is slightly different from the synchrotron tune of the positrons. As a consequence the synchro-betatron resonances are found at slightly different places in the tune diagram for positrons and electrons. Since the losses at 20 GeV are mainly due to synchro-betatron resonances this difference in synchrotron tune can explain why the slightly stronger beam becomes unstable first.

5 Conclusions

The tune shift due to the beam-beam effect that was measured in the strong-weak regime corresponds very well to the theoretical calculation. The tune split in the strong-strong case seems to be systematically higher than the linear tune shift for all values of the separation between the two beams. In the case of separated beams the beam-beam limit seems to be lower than for head on collisions. This was observed in the experiments at 20 GeV and was confirmed with another experiment at 46 GeV, where the measured blow-up increased significantly after introducing a small separation.

For the future operation of LEP it is expected to collide bunches with higher intensities as well as to run with more than four bunches per beam. The separations scheme will have to be upgraded and the experiments reported here will be helpful for the design of the future separation schemes.

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