Experimental study of electron positron collisions in LEP with a finite crossing angle

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Abstract

The beam-beam interaction at a finite crossing angle can excite satellite resonances since it couples the longitudinal and transverse particle motions. The existence of those satellites was shown in calculations and computer simulations and has been demonstrated experimentally at the electron positron storage ring DORIS, where they limited the luminosity. At LEP it is possible to reach crossing angles up to 2.7 mrad in the vertical plane with electrostatic separators, which are normally used to separate the beams at unwanted crossings. This corresponds to a ratio $\alpha\sigma_s/2\sigma_z$ of up to 1.8 where α is the full crossing angle, σ_s the longitudinal and σ_z the vertical beam size. We have studied the behaviour of the vertical beam size as a function of the intensity, crossing angle and betatron tune. Synchrotron satellites of the third order resonance could be observed. We discuss the results and the possibility to use the crossing angle at LEP to increase the number of bunches and therefore the luminosity without increasing the linear beam-beam tune shift.

1 Introduction

Synchro-betatron resonances or satellite resonances can be excited when the transverse motion is coupled to the longitudinal motion and the relation

$$nQ_x + kQ_z + mQ_s = p$$

is satisfied by the betatron tunes Q_x, Q_z and the synchrotron tune Q_s where n, k, m and p are integer numbers. One of the effects that can drive synchro-betatron resonances is the coupling due to the beam-beam effect at a finite crossing angle since the beam-beam interaction seen by each particle depends on its longitudinal position in the bunch. Such satellite resonances have limited the luminosity at the storage ring DORIS [1] and have been studied analytically and by computer simulations [2, 3]. After this bad experience with DORIS, no electron positron storage ring operated with a crossing angle. However, it is not yet understood which maximum crossing angles can be tolerated. The new proton colliders SSC and LHC are foreseen with a crossing angle and simulations have been performed [4, 5] and measurement were done at the SPS proton antiproton collider [6].

The motivation for an experiment at LEP was twofold: first to understand the phenomenon better and secondly to study the possibility to increase the luminosity at LEP with little changes by injecting a short train of several bunches following each other closely and use a crossing angle at the interaction point to avoid unwanted collision and therefore keep the beam-beam tuneshift constant.

Future accelerators such as B-factories require very high luminosities and these could be achieved with a large number of bunches and a finite crossing angle [8].

In this note we report on the measurements and discuss the results.

2 Machine conditions and parameters

To minimise the distortion of the beam by multiple beam-beam interaction we have only injected one bunch of electrons and positrons respectively. The standard optics was used for the experiment. The transverse beam size was measured with the synchrotron light monitors and the beam life time with the beam current monitor (BCT).

Beam separation

The required beam separation for this study was determined by two parameters: first the ratio $\alpha\sigma_s/2\sigma_z$ should be large enough (≥ 1.0) in order to get a strong coupling between the transverse and longitudinal motion and secondly, we wanted to study the beam behaviour at an angle large enough for a possible injection of many bunches. That is, the separation should be large enough that the bunches are not strongly affected by the residual long range beam-beam interaction [7]. It was therefore decided to study crossing angles between 2 and 3 mrad. In all formulas α is the full crossing angle, i.e. the angle between the two orbits. The separation was established with the electrostatic separators normally used to separate the two beams during the accumulation and ramping process. Since the normal separation is a closed bump around the interaction point, the polarity of part of the separators had to be changed to allow an asymmetric bump, i.e. a crossing angle between electrons and positrons. First tests with a single beam have shown that full crossing angles of more than 4 mrad can be reached without loosing the beam, but with a reduced life time. For the experiment we needed a reasonable initial lifetime and decided on a crossing angle of 2.6 mrad. Due to the existing hardware, the crossing angle could be established only in the vertical plane which may not be the best choice for a high luminosity collider [8].

Beam dimensions

The experiment was performed at the injection energy and therefore with the injection optics, i.e. with a horisontal β of 5m and a vertical β of 0.21m. This results in a beam size of $\sigma_x \approx 300\mu m$ and $\sigma_z \approx 25\mu m$. The longitudinal beam size was initially 6 mm. With the crossing angle of 2.6 mrad this would give a ratio $\alpha\sigma_s/2\sigma_z$ of only 0.35, i.e. too small for our purpose. It was therefore decided to use wigglers to lengthen the bunches and the experiment was performed with a (calculated) bunch length of 28 mm. Measurements with a streak camera have shown that the calculated values usually agree well with the measurements. This results in a ratio of 1.5 which is large enough to expect strong coupling.

Beam-beam tune shift

The current accumulated for the experiment was between 60 and $100\mu A$ per bunch which is equivalent to about $3.4 - 5.7 \cdot 10^{10}$ particles per bunch. The resulting beam-beam tuneshift is calculated as 0.02 horisontally and 0.01 vertically for $60\mu A$. For the highest current of $100\mu A$ the beam-beam tune shift reaches values up to 0.035 in the horisontal plane. The beam-beam tuneshifts are very asymmetric in the two planes, because the emittance ratio at injection is much smaller than the ratio of the betatronic functions. The consequences of this effect on our measurements are discussed in the next section.

Because the effective beam sise seen by the opposing bunch is much larger with a finite crossing angle, the beam-beam tune shift is reduced once the crossing angle is established. The effective vertical beam sise is approximately twice as large. The theoretical values for the vertical beam-beam tune shift is then $\xi_z = 0.006$, the horisontal tune shift is almost unchanged.

The normal beam-beam limit in LEP in the head-on case is believed to be around $\xi_{lim} \approx 0.03$.

3 Results

We performed two types of measurements: first we measured the accumulation and beam sise at a fixed value of the vertical tune as a function of the beam current. That is to understand the beam-beam limit under these conditions. To identify the satellite resonances, we have performed a scan of the vertical betatron tune between fractional tune of 0.2 and 0.3, i.e. we looked for satellites of the type $3Q_z + mQ_s = 1$ which should appear as an increase of the vertical beam sise and affect the lifetime of the beams.

Accumulation with crossing angle

The Fig.1 shows the accumulation of the electron and positron beams with and without a crossing angle,i.e. the observed vertical beam sise is plotted as a function of the accumulated current. This is not a normal operational mode since normally the two beams are separated everywhere during the injection process. The onset of the effects of the beam-beam limit should

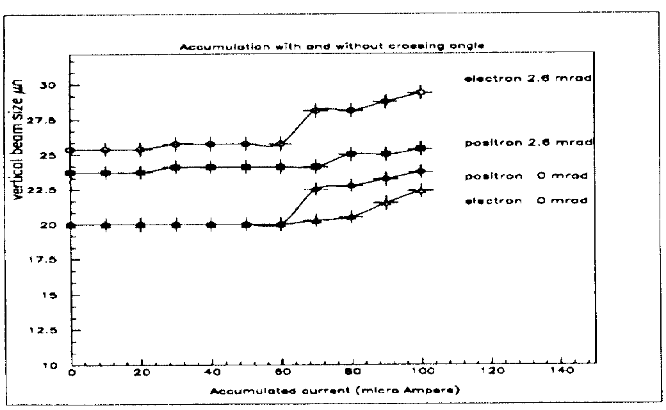

Figure 1: Accumulation with and without crossing angle

appear as an increase of the beam sise. The tune is measured and kept constant during this accumulation process. In order to keep roughly the same intensity in the electron and positron bunches, the bunch equalisation system is used during the accumulation process. Around currents of about $60\mu A$ one observes a clear rise in the vertical beam sise, indicating a blow up due to beam-beam effects. A difference in the behaviour with and without crossing angle cannot be observed. This is understandable if the beam-beam tune shifts ξ_x and ξ_z are calculated: only the vertical tune shift is affected strongly by the crossing angle. However, due to the asymmetric tune shifts caused by the emittances ratio at injection, only the horisontal tune shift is large enough to reach the beam-beam limit ($\xi_x = 0.03$ at $100\mu A$) and we therefore expect no change in the behaviour of the beams at large currents.

Vertical tune scan with crossing angle

The next step to identify the effects due to the crossing angle is to scan the vertical tune and identify the satellites by increase of the beam sise or a bad life time. In the present experiment the horisontal tune was kept constant and the fractional vertical tune was varied from 0.19 to 0.31. This tune range covers the satellites of the type $3Q_z + mQ_s = 1$ with m = 1 and m = 3. The tune scan was performed twice: once without a crossing angle for comparison and a second time with the crossing angle of 2.6 mrad. The observed differences should be due to the crossing angle. The results are shown in Fig.2. The vertical beam sise as observed with the synchrotron light monitor is plotted as a function of the fractional vertical tune. One can

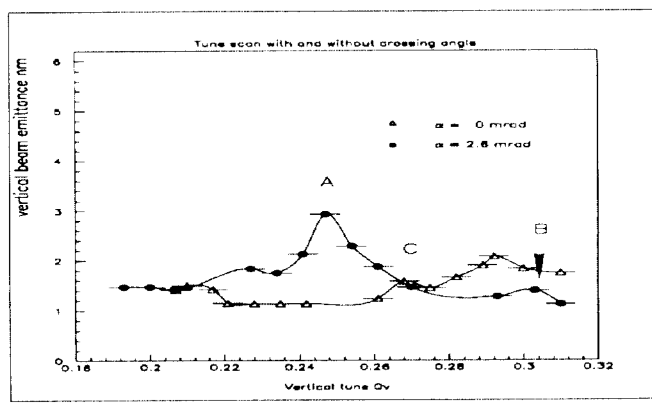

Figure 2: Vertical tune scan with and without crossing angle

clearly identify several regions of interest. In the region A a strong increase of the vertical beam sise is observed which is explained by the satellite $3Q_z + 3Q_s = 1$ which is exactly at this tune value. Without a crossing angle no increase is observed. The life time of the bunch was affected and decreased from 11h to less than 1 h. Such a blow up is expected from simulations and calculations.

In region C a increase of the beam sise is observed in the case without a crossing angle. It coincides with a slightly worse beam life time. We believe that it is due to the excitation of the synchro-betatron resonance $Q_z - 3Q_s = 0$.

A last region with a different behaviour is seen in the region B where the bunch is slightly increased in the vertical plane but the life time is very bad, i.e. significantly less than one hour. A blow up of the bunch core due to the satellite $3Q_z + 1Q_s = 1$ is consistent with these observations.

4 A e+e- collider with a finite crossing angle

Requirements for the beam separation

For a distance from the interaction point much larger than the β-function at the interaction point ($L \gg \beta^*$) the beam sise increases linearly as well as the separation of the two orbits. The separation is therefore approximately constant and is $\approx \alpha^*\beta^*/\sigma^*$ (e.g. [7]). However, because of small β^* values in the vertical plane, it is much easier to obtain the required separation with a horisontal crossing [8]. Assuming the standard optics parameters for LEP (with 90^o phase advance per cell) with $\epsilon_x = 13$ nm, $\epsilon_z = 0.8$ nm and a $\beta_x^* = 1$ m one can compute a minimum crossing angle of about 1.1 mrad if a separation of 10σ is required which seems to be a value which can be accepted [8].

The strength parameter used to characterise synchro-betatron coupling then becomes $\alpha^*\sigma_s/2\sigma^* \approx 0.15$, which is much smaller than the value investigated in our experiment.

With the existing hardware however, only vertical crossing angles can be established and for a separation of 10σ (normalised to the horisontal beam sise), a synchro-betatron coupling strength $\alpha^*\sigma_s/2\sigma^* \approx 0.8$ is found, which is still much smaller than the value we reached in our experiment. This corresponds to a full crossing angle of 1.2 mrad.

A high luminosity collider with a crossing angle

Several proposals were made for electron positron colliders with a very high luminosity to serve as a B-factory [9]. To achieve luminosities in the range above $10^{34}cm^{-2}s^{-1}$ two beams with a large number of bunches are brought into collision. In order to reduce the total beam-beam effect, the emittance of those colliders is usually relatively high to keep the beam-beam tune shift below the maximum possible value while a high bunch intensity is reached. With a crossing angle at the collision point, the emittances of the bunches can be reduced since only a few parasitic collisions contribute to the total beam-beam effect. All the considerations presented above also apply for such a scheme, in particular the requirements on the maximum and minimum crossing angle. Should the required crossing angle not be acceptable since the excitation of synchro-betatron resonances becomes too strong, a crab crossing scheme could be employed. If the crossing angle is not too large, the necessary fields in the crab cavities are reasonably small. In order to optimise the layout for such a scheme, the dedicated design has to be made for a geometry with a crossing angle.

Possible layout with short bunch trains in LEP

The radio frequency in LEP is 352 MHs and therefore the bucket distance is ≈ 0.85 m. Should a bunch train be injected into LEP where the bunches are injected into every third bucket, the bunch distance would be about 2.5m and the parasitic long range collisions would occur every 1.3m away from the interaction point. That close to the interaction point the approximation $L \gg \beta^*$ is not valid and the correct beta-function has to be taken into account. This slightly increases the necessary crossing angle to about 1.6 mrad. The excitation of coupled bunch instabilities could be a severe problem and would need detailed investigations but is not treated in this paper which focuses only on the beam-beam aspect of the interaction. The hardware setup with a superconducting quadrupole about 5m away from the interaction point allows to inject a bunch train of maximum four bunches, since we would like all parasitic collisions to occur before the first quadrupole. In the best case, we could therefore hope for an increase of the luminosity by a factor of four. The estimation of possible background coming from the beam passing through these quadrupoles off centre needs to be studied experimentally.

5 Conclusion

We have studied the beam-beam effects induced by a crossing angle and the feasibility to implement collisions at a crossing angle in LEP and came to the following conclusions:

- Electron positron collisions at a crossing angle can easily be established at LEP with crossing angles up to 3 mrad. The accumulation rate is still acceptable.
- The excitation of low order synchro-betatron resonances which are due to the beam-beam effect at a finite crossing angle can be observed in LEP.
- A possible scheme with a crossing angle to inject more bunches seems possible but would need many more detailed studies and investigations.
- Collisions at a crossing angle for future accelerators operating with many bunches (B-factories) should be envisaged as a possible alternative.

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