Experimental Observation of Synchro-betatron Resonances in LEP

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Abstract

The resonant condition and the strength of synchro-betatron resonances of the type $kQ_h + mQ_v + nQ_s = p$ have been measured by recording the variation of the transverse beam size while traversing these resonances. Measurements have been made as a function of bunch intensity, dispersion and orbit displacements at the RF cavities, vertical chromaticity, synchrotron tune (Q_s), and betatron coupling. A comparison is also shown to illustrate the influence of the Pretzel scheme on the strength of these resonances.

1. INTRODUCTION

In all electron-positron storage rings, synchro-betatron resonances are a potential source of loss of performance due to emittance increase or even beam loss. In LEP these resonances have been a source of intensity limitation at injection energy and a cause of beam loss at collision energies [6]. This has necessitated careful control of the tune values at injection, during energy ramping and in collision.

There are many well known mechanisms for coupling the longitudinal and transverse motion of the particles. Of these, usually the most severe is momentum dispersion at the location of the RF cavities [1], [2], [3]. Consequently LEP was designed with zero horizontal momentum dispersion in all the RF straight sections and of course zero vertical dispersion everywhere. However measurements have shown that the residual dispersion, produced by machine imperfections is significant and particularly dangerous in the vertical plane.

In the future LEP will be operated with a very high Q_s at injection energy in order to increase the threshold for the Transverse Mode Coupling Instability. This scheme may necessitate the traversal of higher-order synchro-betatron resonances due to the reduction in Q_s during energy ramping caused by the limitation in the RF accelerating voltage. It is also envisaged to operate LEP with trains of bunches. This scheme will require vertical orbit displacements at the location of some of the cavities and thereby excite "Sundelin" resonances [5].

2. MEASUREMENT TECHNIQUE

The horizontal and vertical tunes are incremented in a prescribed way by variation of the currents in the main quadrupoles ("tune scan"). At each incremental step the tunes are measured along with the beam sizes (as measured from the synchrotron light monitor), the bunch currents and the current lifetime. In order to differentiate between coherent and incoherent resonant conditions, the tune dependence on current is systematically measured beforehand under identical operation conditions.

3. DEPENDENCE ON BEAM CURRENT

Vertical tune scans were made at three intensity levels. The results are shown in Fig. 1.

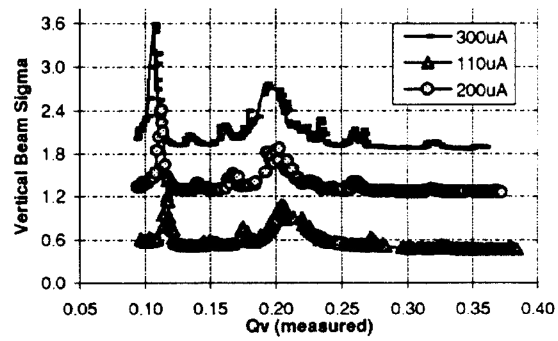

Figure 1. Vertical beam size (arbitrary units) as function of the **measured** vertical tune value.

From the previously measured tune dependence on bunch current the incoherent (zero current tune) values (Q_{vinc}) were calculated. It is also known in LEP that, although the coherent (measured) **synchrotron** tune (Q_s) remains constant with intensity, the incoherent synchrotron tune increases with bunch current. If the hypothesis is made that for example the resonance $Q_v = 3Q_s$ is a single particle resonance and therefore occurs at **incoherent** tune values then by varying the value of Q_{sinc}, a perfect resonant condition can be found for various values of bunch current. The results of this procedure are shown in Fig. 2

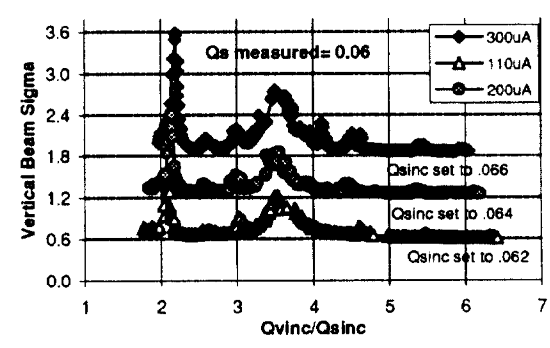

Figure 2. Tune scans at Different Bunch Currents

From Figure 2 it can be seen that there are resonances which are not at an integer of Q_{vinc}/Q_{sinc}. The large, wide resonance appearing between the 3rd and 4th sideband can be clearly identified as the main coupling resonance ($Q_h - Q_v = p$). In order to try to identify the resonance condition for the others, the beam size was also plotted as a function of the difference in the **measured** horizontal and vertical tunes normalised to the **measured** synchrotron tune $(Q_{hm} - Q_{vm})/Q_{sm}$. The results (in Figure 3) show that there are resonances which satisfy the condition $Q_h - Q_v = \pm Q_s$. In addition there are some peaks which do not fit any simple resonance condition.

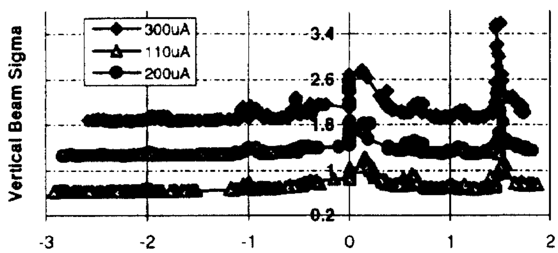

Figure 3. Tune scans at Different Bunch Currents

From the results in Fig. 2 a plot can be made of the shift of the incoherent tune as a function of the bunch current. These results are shown in Fig. 4 and are in good agreement with independent measurements of the same parameter.

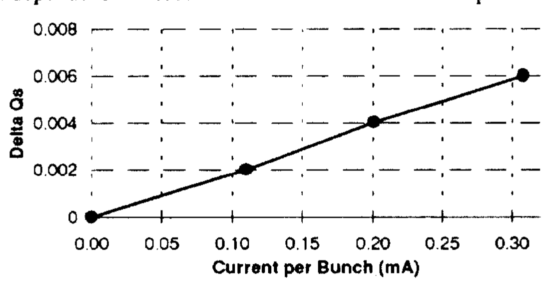

Figure 4. Incoherent synchrotron tune shift vs bunch current

4. INFLUENCE OF VERTICAL DISPERSION

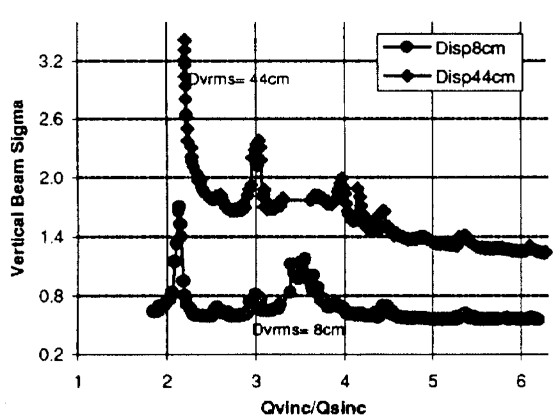

Figure 5. Tune Scans with Two Values of Dispersion

The residual vertical dispersion in the RF straight sections is the main mechanism for coupling longitudinal motion into the vertical phase plane. In normal operation of LEP this dispersion is minimised by careful correction of the closed orbit. For the results presented thus far the measured vertical rms dispersion was 8 cm. In LEP the application of "asymmetric" orbit bumps through the interaction region creates a dispersion "bump". Using this technique the residual vertical rms dispersion was increased from 8 cm to 44 cm. During the subsequent tune scan most of the beam current was lost while the tune was swept across the "second side-band" ($Q_v = 2Q_s$). The tune scan in going from high tune values downward towards and eventually across the second side-band is shown in Fig. 5 along with the tune scan at lower dispersion. Clearly the higher dispersion increases dramatically the influence of the 2nd, 3rd and even the 4th sideband.

5. INFLUENCE OF BETATRON COUPLING

On several occasions in 1991 and 1992, it was observed that the synchrotron side-band of the main coupling resonance ($Q_h - Q_v = Q_s$) can limit the bunch intensity. It is also clear that one of the driving mechanisms behind this resonance is the strength of the betatron coupling. In LEP this quantity is measured by the "closest tune approach" whereby the vertical and horizontal tunes are swept through each other and the tune range over which the tunes lock onto each other is a measure of the strength of the main coupling resonance. In all the experiments reported thus far the measured value for this parameter was .009. For this experiment skew quadrupoles were excited to increase the coupling bandwidth to .021.

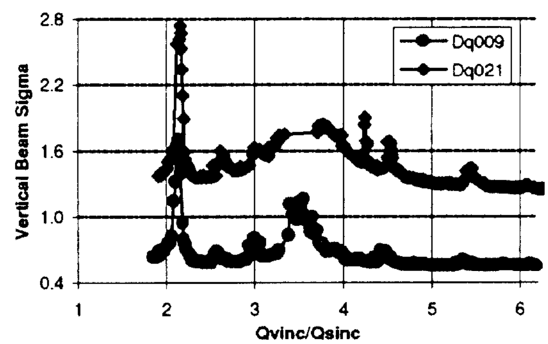

Figure 6. Tune Scans with Increased Betatron Coupling.

Figure 6 shows the tune scan under this condition and, for comparison, the standard tune scan. It is clear that, with the present LEP optics (90° phase advance per cell in the horizontal plane and 60° vertically) the increase in the betatron coupling does not significantly increase the second order resonance or indeed the sidebands of the main coupling resonance (located between the 2nd and 3rd sideband). The bandwidth of the main coupling resonance is of course increased. It is also interesting to note that some of the higher order sidebands have an increased effect.

6. INFLUENCE OF ORBIT DISPLACEMENTS IN THE RF CAVITIES

Synchro-betatron coupling can also be excited by longitudinal fields which have a transverse gradient [4], [5]. This effect can be produced when the beam passes off-centre through an RF cavity. In order to study this effect, magnetic bumps with peak amplitudes of 10mm were generated in all straight sections occupied by RF copper cavities. Figure 7 shows tune scans with zero and 10mm offsets in these straight sections. It is clear that with such large offsets, the 3rd, 4th and 5th sidebands are greatly enhanced.

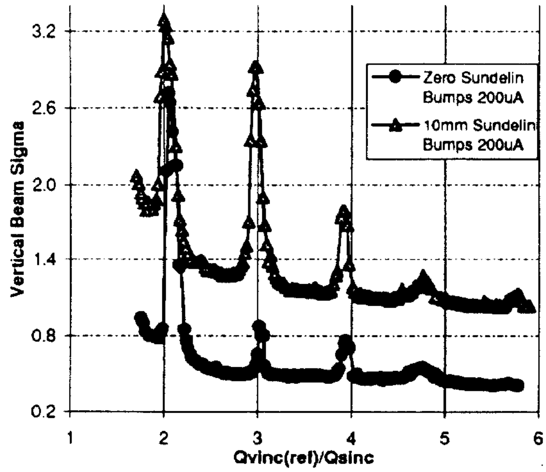

Figure 7. Influence of Orbit Off-sets in the RF Cavities.

7. Influence of the Pretzel

LEP has been operated for the past two years with a "Pretzel" scheme which distorts the electron-positron orbits between the experimental interaction points in order to avoid beam-beam interactions in mid-arc. In this experiment, tune scans were performed with the electro-static Pretzel separators turned on and off. The results, shown in Fig. 8, show that the bandwidth of the second and, to a less extent, the 3rd sidebands are significantly increased.

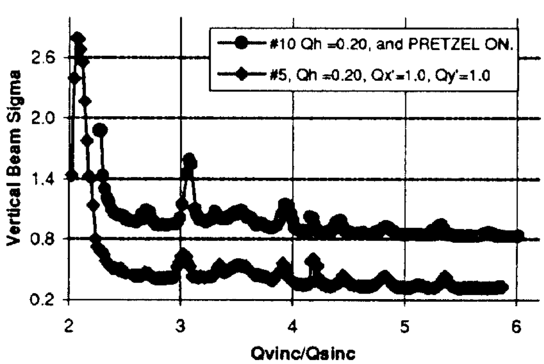

Figure 8. Influence of the Pretzel

8. Influence of the Synchrotron Tune

The fundamental limitation to the intensity at injection in LEP is due to the Transverse Mode Coupling instability whose threshold is proportional to Q_s. Consequently, maximising Q_s at injection by using the maximum available RF voltage maximises the beam current. However with constant RF voltage, the Q_s decreases with energy, thereby causing synchro-betatron resonances to be approached and even crossed. In this experiment tune scans were performed at the maximum value of Q_s and two lower values. The results of Fig. 9 show that the strength of the sidebands increase with increasing Q_s. For very high Q_s (.111), additional resonances appeared at sidebands of the half integer and are visible at values just under 4 on the abscissa of Fig. 9.

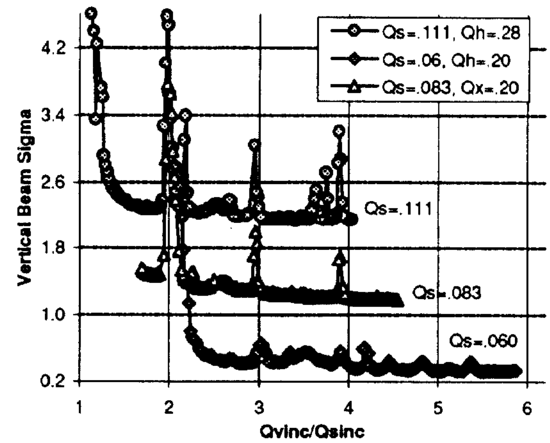

Figure 9. Variation of Synchrotron Tune (Q_s)

9. Summary of Results

A brief summary of the results obtained thus far with experimentation into the parameter dependence of synchro-betatron resonances in given below.

- There was no measurable effect of **horizontal** synchro-betatron resonances. (Plots are not shown here)
- The strongest and most dangerous resonance measured was the $Q_v = 2Q_s$ where **all** tune values are **incoherent** or single particle tunes. The bandwidth of this resonance increases with bunch intensity, vertical dispersion, orbit displacement in the RF cavities, pretzel, and with increasing Q_s.
- In order to fit the resonance condition for $Q_v = 3Q_s$ the incoherent synchrotron tune must increase with intensity as shown in Figure 4.
- The sidebands of the main coupling resonances ($Q_h - Q_v = nQ_s$) are not strongly excited with this optical configuration. However the resonant condition is clearly satisfied by the coherent (measured) tunes.

Increasing Q_s augments the strength of the resonances although at the intensity levels used there remained a lot of resonance free space due to the large value of Q_s. Resonances were observed whose resonant condition has not yet been clearly identified.

10. References

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