Synchro-betatron resonances in LEP

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Abstract Large e^+e^- storage rings generally suffer from various couplings between the synchrotron and betatron modes of particle oscillation which are particularly strong when the corresponding tunes are close to resonance. Studies of the beam dynamics in LEP have identified them as a limitation on the single-bunch intensity. By means of variations of the dispersion functions and orbits in the RF cavities it has been found possible to improve beam lifetime and the accumulated current. We comment on the rôle of wakefields in driving synchro-betatron resonances.

1 Introduction

Synchro-betatron resonances (SBRs) can be excited when the betatron and synchrotron tunes satisfy a resonance condition of the form

$$k_1 Q_x + k_2 Q_y + k_3 Q_s = p, \qquad p, k_{1,2,3} \text{ integers.} \tag{1}$$

In practice, the most significant resonances for most e^+e^- storage rings are the synchrotron sidebands of the integer betatron resonances:

$$Q_x + k_3 Q_s = p, \qquad Q_y + k_3 Q_s = p. \tag{2}$$

They can be driven by non-zero dispersion [1] and the interplay of off-centre closed orbits and the field distribution [2] in the RF cavities. Other driving mechanisms exist when beams are colliding but we shall not consider them here. This paper is concerned with the first studies of SBRs as a limitation on beam current at injection energy (20 GeV) in LEP.

Expectations from LEP design phase In the design phase of the LEP collider, the single bunch intensity was dictated by the threshold of the transverse mode coupling (or fast head tail) instability [3]. It was calculated that the estimated threshold current of 0.75 mA/bunch could be obtained only after the following steps:

- reduction of the β function in the RF sections
- minimization of transverse impedance, design of new bellows ...
- increase of the synchrotron frequency
- use of wigglers at injection to increase the natural bunch length

On top of this a transverse feedback system has been installed to control the coherent betatron frequency so as to prevent mode coupling [4].

LEP was designed with vanishing horizontal and vertical dispersion in the RF cavities but there was expected to be some residual dispersion because of machine imperfections. Simulations concerning SBRs in LEP which are driven by non-zero dispersion in the RF cavities indicate a vertical beam blow up at the first, second and third synchrotron sideband ($k_3 = -1, -2, -3$ in (2)), [5]. Larger energy spread, and thus larger bunch length increase the effect driven by dispersion in the cavities [1,6]. Smaller values of Q_s are also undesirable since they leave little space in the betatron tune plane between the sidebands. Longitudinal wakefields, too, were expected [5,7] to increase the excitation of these resonances. They increase the non-linearity of the RF potential and cause higher synchrotron sidebands of the integer betatron resonances to be excited more strongly.

Experience at other large rings Before the start up of LEP, synchro-betatron resonances were observed in SPEAR II, PETRA and in TRISTAN [8,9,10,11]. The resonances of these four storage rings have the following common properties:

- The transverse bunch dimensions can be enlarged by several standard deviations and the life time can be reduced to a few seconds.
- With decreasing current the strength of the resonance goes to zero.
- All resonances are weaker at higher energies.
- The resonance strength depends strongly on the closed orbit.
- The resonance strength is not affected by changes of chromaticity.

Two types of orbit bumps were used at PETRA to compensate the strength of the satellite resonances. Bumps of the first kind are in the cavity, the others are in the interaction regions producing a large dispersion in the whole machine. Similar methods were used at TRISTAN.

The SBRs at PETRA and TRISTAN have been explained by dispersion and transverse fields which vary with the longitudinal particle position. At SPEAR transverse betatron coupling and orbit distortions were thought to be responsible for the resonances.

2 Working points and maximum current

Early studies of SBRs had to rely on the maximum accumulated current as the main figure of merit indicating the avoidance or compensation of SBRs. Some other information was available from synchrotron light monitors. Experiments were therefore time-consuming and difficult to interpret since injection conditions could vary considerably. Nevertheless, it was found that there was a strong correlation between the maximum storable current and the distance of the measured tune from SBR lines.

The vertical dispersion is large in LEP [12], around 20–40 cm compared with expectations of < 10 cm. This leads one to expect that corrections of the dispersion at the cavities may help. Early on, some attempts were also made to improve accumulation with dispersion bumps in the cavities and appeared to have some beneficial effects; see also Section 4.

A search for a better operational working point found that it was important to keep the measured *coherent* tune clear of both 3rd and 4th order synchrotron sidebands. With $Q_s = 0.082$, the move from $(Q_x, Q_y) = (0.375, 0.290)$ to $(0.280, 0.190)$ in the region between 3rd and 4th order sidebands produced an improvement in peak current and accumulation rate.

3 Dependence of beam height on tunes

The wire scanner in LEP monitors the vertical beam size of individual bunches. Because of calibration problems of the speed of the wire passing through the beam, the absolute value given for the beam size is not necessarily the real one. Nevertheless the relative blow up of the vertical beam size can be observed as the vertical tune is varied.

The betatron tunes were varied by making small changes to the excitation of the main (QF and QD) quadrupole strings in the arcs and the new values measured with the Q-meter [13]. Of course the Q-meter always measures the *coherent* tune. Note that the incoherent tunes are always *higher* than the coherent ones [14]. Figure 1 shows the path taken by the *coherent tunes* during an experiment in which the vertical beam size was measured with a single bunch in the ring. The bunch current $I_b \simeq 0.2\,\mathrm{mA}$ did not change by more than 10% until the end of the experiment as the $k_3 = 2$ sideband was approached from above. At this current the coherent tune shifts are [14]

$$Q_x^{(\mathrm{coh})} \simeq Q_x^{(\mathrm{inc})} - 0.012, \qquad Q_y^{(\mathrm{coh})} \simeq Q_y^{(\mathrm{inc})} - 0.024. \qquad (3)$$

The variation of σ_y is shown on the right of the plot. It clearly shows the excitation of the second and the third sideband. What was unexpected is that the blow-up occurs when the *coherent* tune is close to the resonance. Previous understanding suggested that resonances driven by dispersion or closed-orbit in the cavities were *incoherent*. In fact the peak in the beam size at the third sideband is not perfectly centred on the coherent resonance line but the incoherent resonance condition is still further away.

To test this conclusion, Q_s was changed to 0.074 by reducing the RF voltage, just after crossing the resonance from above (when $Q_x = 0.293$, $Q_y = 0.216$) and the σ_y had been reduced. This brought the sideband lower and increased σ_y again. Similar tests, using qualitative information on the beam size from the synchrotron light monitors were done in the search for a good working point mentioned above.

4 Compensation of dispersion at RF cavities

Since it is still difficult to measure the dispersion with adequate resolution [12], our attempts to cancel the dispersion at the cavities could only be by trial and error.

Attempts to reduce the vertical beam size were made with the help of vertical dispersion bumps. Four tilted quadrupoles around Point 2 or Point 6 (where the RF is located) were used to couple the horizontal dispersion into the vertical plane. The amplitude and the phase of the dispersion bump gave two free parameters which could be adjusted to compensate the dispersion in the RF cavities.

The following experiments were also based on monitoring the vertical beam size with the wire scanner.

Experiment A Following on from the tune variation study described above it was found that the beam size could be reduced by choosing the right phase of the bump. The amplitude of coherent transverse signals observed in the transverse feedback system pickup was correlated with this providing additional confirmation of the coherent nature of the resonance.

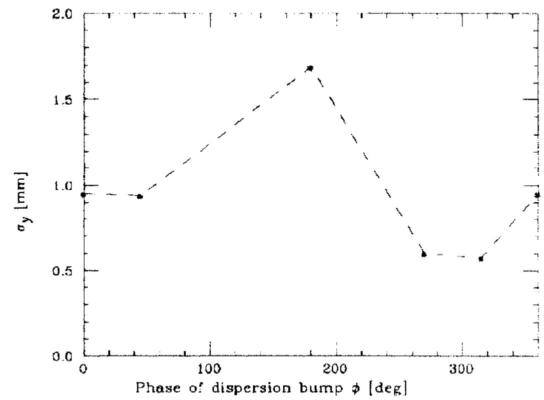

Figure 2: Vertical beam size versus phase of dispersion bump.

Experiment B The working point was chosen close to the third order sideband to increase the excitation. Since changes in the bump might change the tunes, these were measured and corrected back to the values (0.283, 0.224) at each step in order to maintain the resonant condition (this was not done in Experiment A).

Figure 2 shows the variation of the vertical beam size for different phases of the bump. The amplitude was kept constant at 10 cm in the RF section, reaching a peak value of 36 cm in the superconducting low-β quadrupoles.

5 Conclusions and Outlook

A tentative explanation of our observations might be that the persistent coherent longitudinal dipole motion [14] which is a feature of LEP's longitudinal phase space is coupled directly into the transverse motion through dispersion at the cavities. Since high current levels in LEP also require very good steering of the orbit through the centres of the RF cavities, it is very probable that resonances driven by closed-orbit deviations in the cavities also play a rôle.

Although there were at times some difficulties connected with the absolute measurement of the vertical beam size in LEP, it became clear [12] that the anomalous betatron coupling due to the nickel layer on the vacuum chamber was not enough to explain the vertical beam size, particularly at injection. It now seems likely that coherent synchro-betatron resonances account for the greater part of this discrepancy. Coherent vertical motion of the beam can sometimes be observed.

There is some evidence at present that the incoherent SBRs also play a rôle in LEP, once the current is high enough. Given that the problems are mainly coherent, the strategies for solving them are clear: increasing Q_s to get more space between the SBRs should help; in fact this has already led to new record currents [14]. However this improvement may also be connected with the suppression of the coherent longitudinal motion which occurs when Q_s is small (i.e., $Q_s < 0.1$ in LEP). The reactive feedback system can be operated in order to keep the coherent and incoherent tunes equal—this should make it much easier to avoid both kinds of resonance.

Use of a high Q_s at injection means that there will not be enough RF voltage available to keep Q_s constant during ramping. This will lead to the danger of crossing resonances and it may be necessary to implement a Q-jump [5] in the ramp.

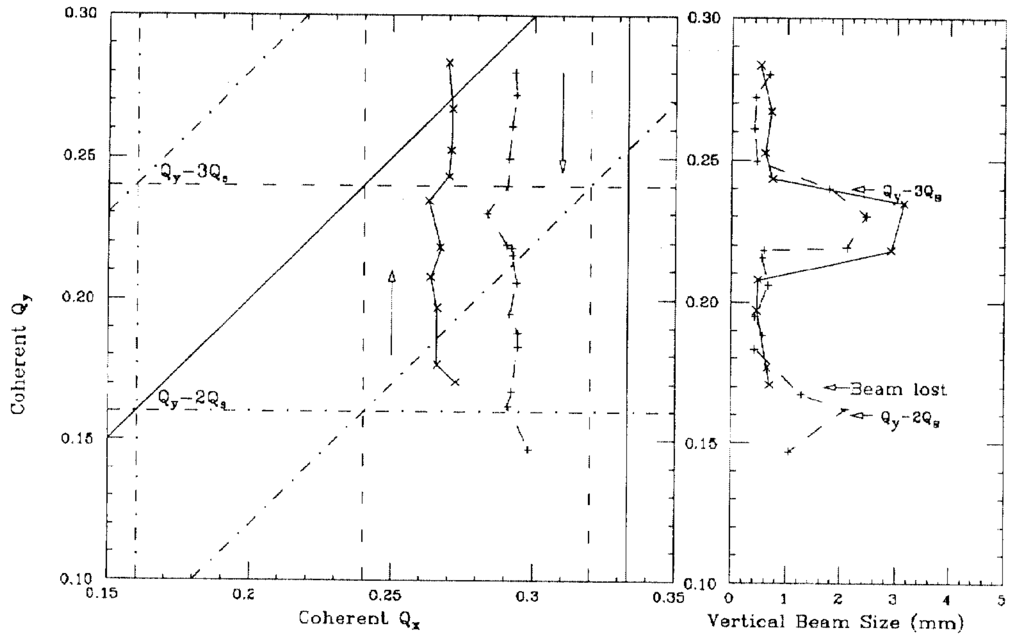

Figure 1: Tune diagram and beam size: the frame on the left shows selected resonance lines in the betatron tune plane. Here and in the text we quote only the fractional parts of the tunes; the integer parts are 71 and 77 and the synchrotron tune is $Q_s = 0.08$. The coupling resonance $Q_x - Q_y = 6$ and the third order betatron resonances are marked as solid lines. Synchrotron sidebands, including (2) are shown as dot-dashed lines as are the first synchrotron sidebands of the coupling resonance $Q_x - Q_y \pm Q_s = 6$. Two segments on the path of variation of the measured coherent tunes in the experiment are shown as solid and dashed lines. On each of these, Q_x was more or less constant. The corresponding plots in the right frame give the measured vertical beam size as a function of Q_y.

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