Experimental observations of instabilities in the frequency domain at LEP

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Abstract

The operation of LEP at high energies (LEP energy upgrade) implies the development of a new low emittance lattice with 90 degrees phase advance in the arcs. During the development sessions dedicated to this lattice, it was established that the maximum accumulated intensity was strongly depending on the actual bunchlength. Wigglers are used to artificially lengthen the bunch, which otherwise would be extremely small in this lattice (σ_s=3mm). Depending on the wigglers settings, we could observe the onset of vertical instabilities (among which a transverse m=1 head-tail instability) at different thresholds. These did coincide with the appearance of additional spectral lines in the longitudinal plane, whose frequencies were clearly intensity dependent. A preliminary analysis of both the identification and the behaviour of these spectral lines is presented.

1 INTRODUCTION

During the first few attempts to operate LEP with a 90° optics, it was systematically observed that the accumulated current was severely limited by a fast and strong transverse instability occuring around 150 μA. Since such a low emittance lattice is essential for the operation of LEP at high energies in order to increase the luminosity, a lot of effort has been dedicated to the understanding of these instabilities. The subsequent machine development sessions enabled us to establish that the intensity limitations could be cured (or pushed to a higher threshold) by carefully controlling both the bunchlength and the chromaticity of the machine. Most of our understanding of the mechanisms involved resulted from the simultaneous observation of three instruments, namely a streak camera, a longitudinal and a transverse spectrum analyzer. The combined use of these instruments enabled us to clearly identify the onset of a transverse m=1 head-tail mode, which was predicted by theory, but had never been observed so far. At higher currents, we then reached another instability which we believe can be associated to the transverse mode coupling instability (TMCI). Although these limitations clearly occured in the transverse planes, an interesting correlation between the saturation of the accumulated intensity and the appearance of additional lines in the longitudinal plane could be observed. The aim of this paper is not to give a theoretical explanation of the experimental results, but much more to report on observed facts and suggest a direction for their interpretation.

2 TRANSVERSE M=1 HEAD-TAIL MODE

For bunch intensities above 300 μA the vertical m=-1 mode becomes visible in the transverse spectrum without any external excitation of the beam. A pure m=-1 mode should not be apparent on a narrow band low frequency pick-up. However, the impedance introduces some coupling with the m=0 dipole mode so that it finally becomes visible. The parameters (bunchlength and chromaticity) for which the m=1 head-tail instability could be observed are in excellent agreement with the theoretical predictions [1].

3 LONGITUDINAL OBSERVATIONS

A general feature of the longitudinal spectra observed with the 60° optics used for the operation of the machine is that, usually, the second harmonic of the synchrotron frequency (f_{s2}) is the highest harmonic visible. It even disappears once the longitudinal feedback is switched on. A completely different picture can be observed with the 90° lattice. Without feedback, all harmonics up to high orders are visible. Even in presence of feedback and damping wigglers, one can usually still observe all harmonics up to the third one. This intrinsic difference has to be related to the much shorter bunchlength inherent to the 90° lattice. A measurement of the behaviour of the second harmonic of f_s as a function of the bunch intensity is presented in Fig. 1. Actually the same qualitative behaviour has been also measured for the third harmonic. Their positive shifts with increasing intensity nicely confirm the suspected capacitive behaviour of the LEP impedance in the frequency domain involved [2]. The data refer to a case with damping wigglers on ($\sigma_s \approx 10$ mm). The same measurement for f_{s2} without damping wigglers ($\sigma_s \approx 6$ mm) nicely demonstrated the dependence of the detuning on the bunchlength, a much larger slope being seen in this case.

3.1 Spectra versus intensity

All the results presented in the following refer to a situation where the damping wigglers are powered to 400 A, which corresponds to a r.m.s. bunchlength of about 10 mm. The longitudinal feedback is always active.

During accumulation, the behaviour of the longitudinal spectra can be split into five distinct regimes:

1. At low intensity, one observes only one broad line around the coherent synchrotron frequency f_s. This line does not shift with current.

2. Around 190 μA a line emerges at about twice f_s. The frequency of this line is shifting upwards with intensity. The appearance of this f_{s2} line coincides with the onset of quadrupole oscillations of the bunch which can be clearly observed with the streak camera. At the same time, a few additional lines appear around f_{s2} but their spacing always corresponds to 50 Hz so that they will be ignored in the following.

3. Around 270 μA an addditonal line (f_{s1}) appears above f_s. Its frequency is shifted by about + 70 Hz w.r.t. the synchrotron frequency. The appearance of this line coincides with a frequency jump of f_{s2}.

4. Around 300μA the f_{s2} line is suddenly surrounded by additional lines spaced by about 16 Hz. Up to the maximum achievable intensity, these lines shift with current. Despite of a rather restricted range of observation, a careful set of measurements enabled us to establish that the detuning of these lines w.r.t. f_{s2} was increasing with intensity.

5. When reaching the maximumintensity, two additional lines emerge between f_s and f_{s1} spaced by about 34 Hz. This unexpected behaviour is especially interesting in the sense that, whatever the machine configuration, the appearance of these lines around f_s and f_{s1} did coincide with the saturation of the accumulated intensity.

The behaviour of all the regimes of coherent frequencies described above is illustrated in Fig. 2. Note that the vertical scale has been cut to ease the representation.

4 TENTATIVE EXPLANATION

Before any attempt to explain the observed behaviour as a beam effect, it was necessary to convince ourselves that it was not related to some hardware problems. Remembering that additional experiments were not possible until the next start-up of LEP, we carefully discussed our measurements with the people in charge of the feedback system. It followed from these discussions that a hardware artifact seems to be rather unlikely. This is also supported by the fact that the spacing of the lines increases with current which points to a real beam effect.
With this assumption one could envisage the following tentative explanation:
The observed lines are the manifestation of the so-called radial modes which have been predicted by many theories (e.g. [3] [4]) but, to our knowledge, never observed experimentally so far. Due to the potential well distortion, their frequencies become different from the main dipole or quadrupole modes and appear as satellites to f_s and f_{s2}. According to [4], the fundamental modes should degenerate into some kind of a continuum (infinite number) of modes with increasing intensity, whereas our observations are clearly of discrete nature. However, one should remember that only the modes being sufficiently coherent can be observed. On top of this, it was experimentally observed that some additional lines could be detected around f_{s2} after a dedicated fine tuning of the analyzer's settings.

In order to have some better understanding of the observations, a simplified multi-particle model has been tentatively developed. The latter consists in considering the particles of the bunch as a set of harmonic oscillators coupled by a non-linear potential (wakefield effects) and concentrating on the modes of oscillation of the average of the distribution. Very simplified considerations on the solutions of this system of differential equations for a potential of second or fourth degree already reproduce many of the observed lines such as f_s f_{s1} f_{s2} as well as some of the lines surrounding f_{s2}. However, the explanation for the lines emerging between f_s and f_{s1} is not straightforward. This is probably related to the fact that we presently restricted ourselves to the most obvious solutions.
We therefore think that the experimental observations might be consistent with the model of radial modes with two restrictions:

1. According to the model, the radial modes are expected to degenerate into an infinite number of frequencies. In our case, the modes clearly remain of discrete nature.

2. The model predicts both an increasing spacing between the frequencies with intensity and, at the same time, an increase in the relative spacing between the modes (each mode experiences a different shift). The measurements reproduce the overall detuning as a function of current, but the spacing between the lines seems to remain more or less constant. However, due to both the limited observation range of the coherent modes and the relative accuracy of the measurements, it seems difficult to conclude that the measured data conflicts with the model.

In conclusion, assuming that a hardware artifact can be excluded, it looks like the measured data could be consistent with the model of radial modes. Their observation is in itself an interesting effect, however, the possibility of a link between their appearance and the onset of current limitations seems to be even more challenging.

5 TURBULENCE

Typically, the threshold for turbulence is identified as the current above which the bunchlength begins to increase non-linearly. The bunchlength is usually measured with a dedicated pick-up which yields an average over many turns. Consequently, for most of the applications related to collective effects, one observes (measures) that, above the threshold of turbulence, the bunchlength has indeed increased. Since instabilities usually develop over many turns, the concept of using an averaged bunchlength is probably correct for the computation of instability thresholds. However, the streak camera clearly shows that, in reality, this picture is erroneous. As a matter of fact, the modes of oscillation remain of discrete nature, so that the bunchlength steadily oscillates between a large and a small value. The corresponding minimum/maximum values of the bunchlength measured as a function of the intensity are illustrasted in Fig. 3. It thus follows that the behaviour of the bunchlength in the present approach should be clearly differentiated from a real bunch lengthening which can be achieved by other means (e.g. lowering the RF voltage or powering the wigglers).

6 CONCLUSION

The aim of this paper is to report on the experimental observation of coherent modes of oscillation in both the longitudinal and transverse planes. A vertical m=-1 mode could be observed on both the transverse spectrum and the streak camera. The stability of the transverse modes proved to be in excellent agreement with theoretical predictions. In the longitudinal plane, several discrete modes which differ from the usual harmonics of f_s could be observed. When looking at the longitudinal spectra during accumulation (especially around the synchrotron frequency), one observes a coherent frequency emerging at about 60 % of the maximum intensity. At higher current, two additional modes appear on the spectra. This occurence is systematically coincident with either saturation of the accumulation or the onset of a transverse instability.

Due to the limited amount of MD time available with the new 90° optics, it was not possible to perform all the necessary additional measurements which could have helped to better identify these modes and understand their origin. It is thus fair to state that, at present, we do not have enough experimental evidence to completely exclude some instrumental effects which could create such lines on the spectra. According to the present understanding, we believe that these modes could be interpreted as the manifestation of radial modes predicted by theory but never observed experimentally. Such an hypothesis obviously requires to be consolidated by further detailed studies which will be hopefully achieved during the 1992 running period of the LEP machine.

7 REFERENCES

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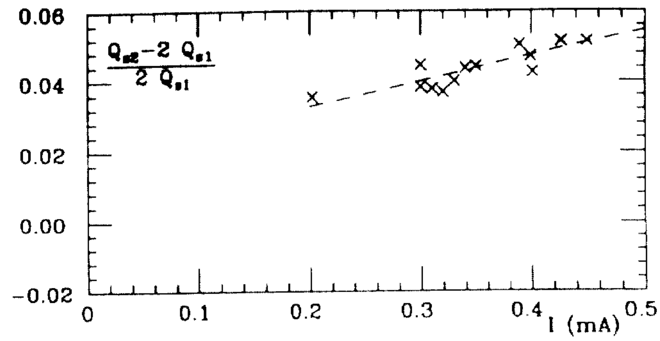

Fig. 1 Relative change of the quadrupole mode frequency.

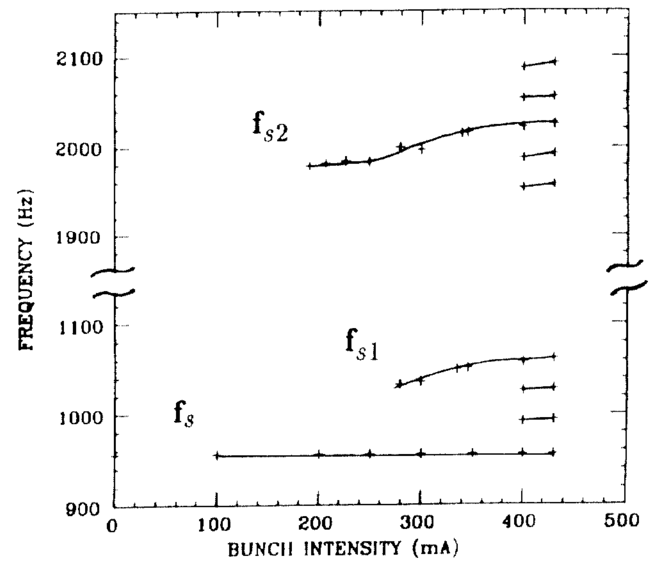

Fig. 2 Modes frequencies vs. intensity.

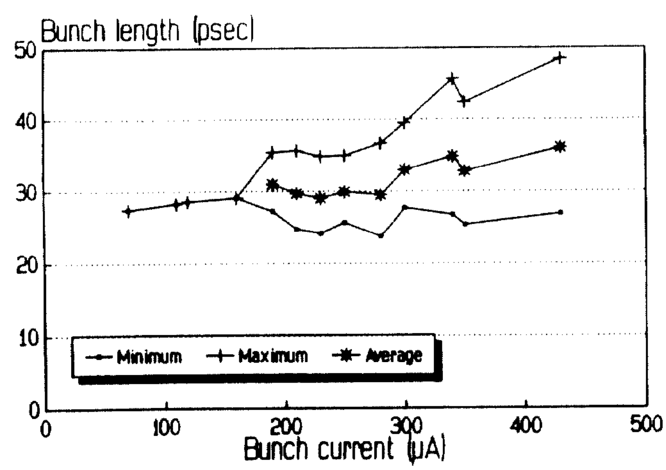

Fig. 3 Bunchlength as a function of current.