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REAL-TIME MONITORING OF BEAM-BEAM MODES AT LEP

O. Berrig, K.D. Lohmann, G. Morpurgo, H. Schmickler

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By slightly exciting one of two colliding bunches in LEP, it is possible to enhance the eigenfrequencies of the resonant system of the two bunches coupled by the space charge force. The LEP Qmeter has been adapted to detect, among these excited frequencies, the so called σ- and π- modes, whose distance is proportional to the luminosity. A real time display of these quantities provides the Operators with an effective way of finely optimizing the luminosity.

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By slightly exciting one of two colliding bunches in LEP, it is possible to enhance the eigenfrequencies of the resonant system of the two bunches coupled by the space charge force. The LEP Qmeter has been adapted to detect, among these excited frequencies, the so called σ- and π- modes, whose distance is proportional to the luminosity. A real time display of these quantities provides the Operators with an effective way of finely optimizing the luminosity .

1 INTRODUCTION AND MOTIVATIONS

The idea of evaluating the LEP luminosity by measuring the tune split between the modes of oscillation of the coherent beam beam effect was first expressed in [1]. This effect had already been studied in other accelerators, see for example [2], [3], [4] and became the object of an operational tool at the TRISTAN MR [6]. We at LEP have recently implemented a similar tool, where the two modes are constantly monitored and displayed on a television screen. While an absolute and accurate evaluation of the LEP luminosity by means of such a tool is highly improbable, the tool can provide an "adviced" Operator with a real time feedback on relative luminosity changes. Such a tool constitutes an additional and effective weapon in the neverending fight to improve the integrated luminosity .

2 SOME THEORY

The phenomena which we are going to treat has been analysed in depth in many places, among which the above mentioned references, so we should limit us to briefly describe it, and to report the main results. Anyway these results have always been obtained by making some approximation and by examining ideal conditions. This makes it difficult using them to produce an accurate quantitative estimation of the luminosity.

When two charged particle beams collide in a storage ring, the space charge of each beam gives the other beam a transverse kick and changes its betatron tune. In other words, the two beams are coupled by the beam beam force. If the beams have opposite electrical charges they are attracted by each other and, in the simplest model, the original beam tune will remain unaffected, while an additional peak with higher tune will appear in the two beam spectra. The two beams will oscillate in phase at the original frequency (called σ-mode, or also 0-mode), and in phase opposition at the new frequency (hence called π-mode). The stronger the beam-beam kick, the larger the distance between the two peaks (this distance is also called the Coherent Beam-Beam Tune Split). We only have two modes if we have one bunch per beam. At LEP, we have 4 interaction points and 4 bunches per beam, forming two almost independent systems of 2+2 strongly coupled colliding bunches. The two systems are weakly coupled via the parasitic encounters halfway between the interaction points. In this case we have 8 different modes of oscillations, but it can be demonstrated that the 0-mode is still close to the original frequency, and that the π-mode is the phase opposition mode most distant from the 0-mode. Therefore the situation is qualitatively unchanged.

Let us now concentrate on a Gaussian "flat" beam, where $\sigma_y << \sigma_x$. In this approximation the **Single Particle Vertical Beam Beam Strength Parameter** ξ_{y_0} is related to the luminosity by the following formula

$$L = \frac{N\gamma f_{rev}\kappa_b\xi_{y_0}}{r_e\beta_y^*}$$

It was then shown ([1],[5]) that in the approximation of a Gaussian beam, the **Coherent Beam Beam Strength Parameter** ξ_y is just 1/2 of ξ_{y_0} . Finally, the dependency of the **Beam Beam Tune Split** ΔQ_π on ξ_y at LEP can be expresses [1] through the nonlinear functions shown in fig.1.

From this picture we can say that, as long as we do not

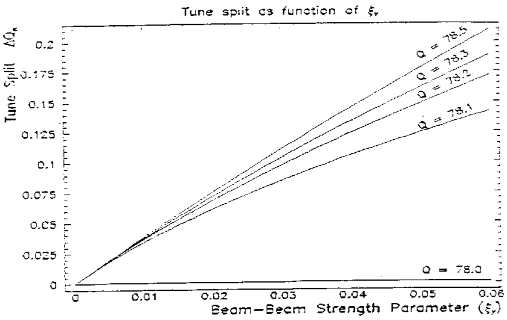

Figure 1: Dependence of the Tune Split Between the 0 and π modes as a Function of the Single Particle Beam-Beam Strength Parameter and for some values of the Unperturbed Machine Tune.

Figure 1: (from reference 1)

change the unperturbed tune, the larger the distance is between the two peaks, the higher is the luminosity. So, if we can monitor this distance, we are able to know immediately how our actions on the machine (orbit corrections, coupling compensations etc.) are effecting the luminosity.

3 THINGS THAT COULD GO WRONG...

In the previous section we have implicitely assumed that the Tune Split (which we can measure) grows when the beam-beam strength parameter (which we cannot measure directly) grows. This is true only in the case when all the other parameters do not change. In the real life this is never

the case, and so we should be very careful before drawing false conclusions. For instance, in order to try to increase the luminosity we might reduce the vertical tune. From fig. 1 we immediately see that for the same beam-beam kick (and therefore for the same luminosity) the Tune Split is strongly dependent on the vertical tune. Therefore, if we reduce the fractionary part of the vertical tune, let's say from .2 to .15, to the same luminosity, or to a slightly increased one, will correspond a lower Tune Split.
Another factor that should be taken into account is that the beam is also subject to parasitic encounters with the other one (in the odd points if we do not run bunch trains, and also close to the interaction points if we run with a bunch train scheme). For simplicity we only consider the case without bunch trains. In this case, the two beams are normally well separated in the odd IPs , and these beam-beam kicks are defocusing (even if much weaker that the kicks in the interaction regions). This can be expressed by the formula [7]

$$\xi_y = -\frac{N r_e \beta_y}{8\pi\gamma y^2}$$

where ξ_y , the tune shift due to the parasitic encounters, is inversely proportional to the square of the separation distance **y**. Any manouver which modifies the separation between the beams in the odd points will have an effect on the measurable Beam-Beam Tune Split, without necessarily changing the luminosity.

4 THE LEP QMETER AND THE BEAM-BEAM DISPLAY

The main difference between the measurement method adopted at LEP and the method implemented at PETRA,CESR or TRISTAN lies in the signal treatment; in all these latter cases the analog signals detected by some beam position monitors are somehow recombined and hardware manipulated before being sent as input to a spectrum analyser and displayed on a screen. At LEP, instead, the Qmeter system can digitize and process via a DSP based system the position data corresponding to every single turn. In particular, a phase preserving FFT can be performed on any convenient number of turns, and a smoothing algorithm to reduce the high frequency noise can be applied. The FFT spectra will be displayed and refreshed continuously on a tv screen. By setting the Qmeter to observe two colliding bunches we can then numerically recombine (add) the two corresponding spectra, after having applied an arbitrary phase shift to one of them. Every frequency component in each of the two spectra can be thought of as a two dimensional vector. The amplitude of a frequency component of the recombined spectrum is obtained by performing a vector sum of these two vectors. By shifting the phases of one spectrum by one degree at the time over 360 degrees, we can put in evidence the phase relationship between the 0- and the π-mode. In fact, when the phase shift is such that the 0-mode in the recombined spectrum finds its maximum, the π-mode, if visible, should be at its minimum. By giving an additional shift of about 180 degrees[1] the situation will be reversed, and the π mode will be enhanced. Until now this has been done by an offline program, any time there was a doubt if the spectrum peaks shown on the tv screen were really the 0- and π modes, but this year the algorithm has been implemented on line.

5 HOW DOES IT LOOK LIKE

The measurement requires a small vertical excitation of one of the colliding bunches. To find the right level of excitation is not always easy. A too large excitation would reduce the luminosity (and the beam-beam tune split), while a too small one will not produce a clean signal. Moreover we would ideally like to have perfectly centered and head-on collisions, and this would also minimize the amplitude of the π-mode peak. Nevertheless we can get some nice data. In fig.2 we show a greyscale plot of the two combined spectra. The x-axis represents the tune, while the y-axis the degrees of rotation of one spectrum respect to the other. The darker the plot, the higher the peak. We can clearly observe the two modes in phase opposition, with the π-mode (just below 0.36) having a maximum when the 0-mode (at about 0.18) has a minimum, and viceversa. Figures 3 and

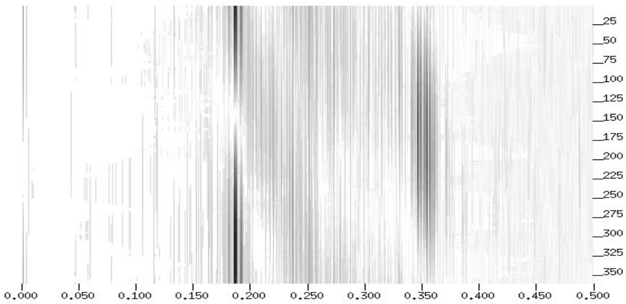

Figure 2: Observation of the 0- and the π-modes (data from 1997)

4 show the same data in another way. What is most useful for the operation of LEP is however the on-line display. The algorithm which is looking at the spectra of the two bunches, trying to find the 0- and the π-mode, has to examine a signal which is not always very clean, and sometimes is hidden by higher peaks. Fig.5, 6 and 7 show respectively the starting spectra (the one excited directly and the one excited by the beam-beam coupling), and the result of the internal computation of the algorithm looking for the π-mode. This procedure correctly finds the highest phase coincidence for the π-mode at around 0.31 (notice how it gives zero probability to the 0-mode at 0.18, because for

[1]The two modes are in perfect phase opposition at the interaction point; at the location where the beam is observed the betatron oscillation corresponding to the π-mode has gained some phase advance compared to the 0-mode, because in one turn of LEP it must gain a phase advance corresponding to the beam-beam tune split. So at that location the difference between the two phases is not exactly 180 degrees.

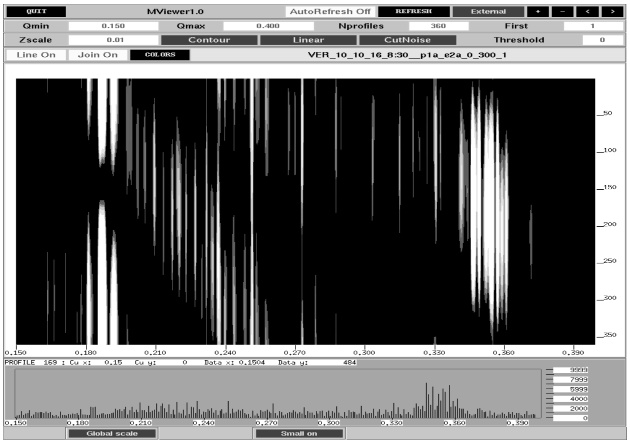

Figure 3: Observation of the 0- and the π-modes : color contour

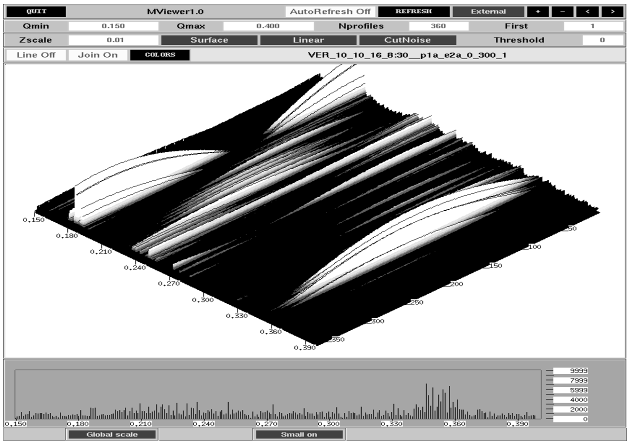

Figure 4: Observation of the 0- and the π-modes : mountain range

this frequency the phase relation expected between the two spectra is clearly non satisfied).

6 CONCLUSIONS

By giving the LEP Qmeter software the capability of comparing the relative phases of the different spectral peaks, we built a tool capable of identifying the sigma and pi modes of the beam betatron oscillation. The complete spectrum, together with the measured value of the tune distance between the two modes, is displayed in real time on a television screen close to the LEP Operator. This information complements well other "luminosity indicators" (like the beam vertical size) and is used by the Operators as a fast indication if their actions are going in the direction of higher luminosity. This enables them to effectively playing with many machine parameters (orbit, tune, coupling, fine adjustment of electrostatic separators, etc.), reaching and mantaining luminosities difficult to achieve otherwise. It can be estimated that such way of operating LEP could increase the integrated luminosity by at least 10% , and this tool was indeed used during in the last period of operation in 1997, both with the well known 90/60 optics and with the newly commissioned 102/90. During this period peak beam-beam tune shifts of 0.056 and 0.053 , and averages around 0.05 lasting for almost one hour, were respectively reached.

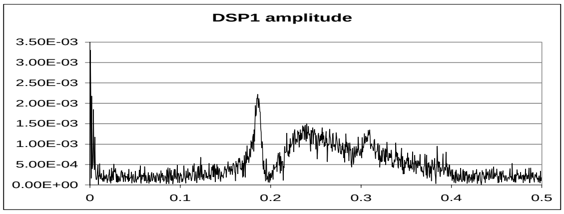

Figure 5: Spectrum of the directly excited bunch

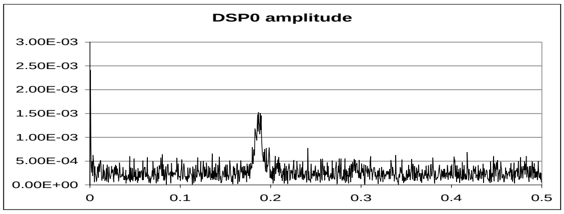

Figure 6: Spectrum of the indirectly excited bunch

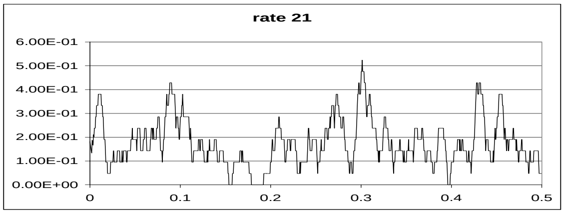

Figure 7: Outcome of the π-mode finder algorithm.The highest peak at 0.31 points to the most probable candidate for the π-mode tune

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