Harmonic Analysis of Coherent Bunch Oscillations in LEP

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Abstract

The Beam Orbit Measuring system (BOM) allows the acquisition in real time of bunches position at the 504 BPM's (PU), for more than 1000 revolutions. These data can then be treated in parallel by 40 microprocessors to yield, after one minute, the amplitudes and phases of the measured oscillations.

Since the bunch and the revolution numbers are recorded during acquisition via the beam synchronous timing, the phase differences obtained from coherent betatron oscillations give directly the true phase advances of the lattice and the measured amplitudes are proportional to $\sqrt{\beta}$. This constitutes a powerful tool to check the machine optics quality prior to physics runs.

Similarly, coherent synchrotron oscillations, excited by an RF phase modulation, have been used in order to measure horizontal and vertical dispersion. Examples of these measurements are given.

1. INTRODUCTION

The BOM System [1,2,3] is one of the most vital instrument in LEP, and is potentially very powerfull. The pickups (PU), connected to 40 VME crates, are distributed all around the 28 km of the LEP ring. The PU signals for each passage of up to 8 electron and positron bunches are processed in the tunnel by 448 analogue normalysing cicuits (Narrow-Band phase processor and 8-bit FADC) and by 56 linear processors (Wide-Band gated fast sample-hold and 12 bit ADC) near the crossing points. The digitized data, together with a turn number distributed by a Beam Synchronous Timing system [4], are stored in special VME memory cards which can record up to more than 1000 turns. The data are then further processed by 40 µPs (DSCs in shielded tunnel locations) and collected in a single computer, an Apollo BOM server, in order to perform trajectory (single turn), central orbit basic measurements, or after multiturn acquisition a harmonic analysis of the trajectories followed by a given bunch both in time or along LEP.

During 1991, major changes were made to the first control architecture of the BOM system [5,6]. The 40 BOM ECAs connected via MIL-1553 to 24 PCA's were converted to "DSC's" (with 68030-based CPU cards) connected directly to Ethernet with 24 IBM Ethernet-Token_Ring bridges. The equipment embedded software that had previously been written in Pascal under the RMS-68K operating system was entirely rewritten in C under OS-9. This upgrade involved the investment of 2 man-years of software effort.

The Multiturn and Harmonic Analysis facilities were commissioned during MDs and after the September technical stop an improved calibration procedure was also introduced. Finally from October until the end of the LEP running period, the new "BOM menu" was commissioned with its access to automatic orbit acquisitions made every minute.

The visual observation of the position plots of 1024 turns from PU to PU, or their FFT analysis, is already a usefull diagnostique tool: for instance, it allowed to observe a significant 50 Hz perturbation (Fig. 1) caused by a 18 kV cable and to locate it, to observe the damping time after a kick or to observe beam instabilities, etc...

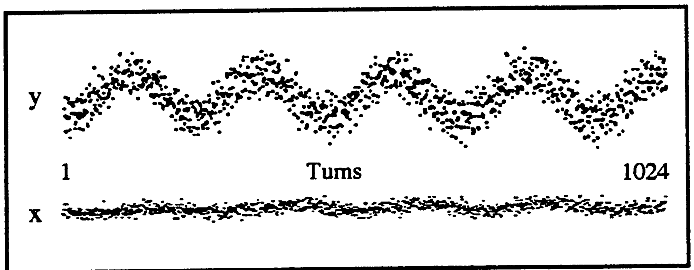

Fig. 1 : Single PU recording of beam vertical 50 Hz oscillation due to a 18 kV cable influence (scale: 0.08 mm peak to peak, time= 88.9 µs/turn)

The harmonic analysis has permitted very useful studies of coherent oscillations. This BOM tool turns out to be particularly powerful to measure with great precision machine optics properties like the phase advance between collision points, beta beating, dispersion, etc.

2. STUDY OF COHERENT BETATRON OSCILLATIONS [7]

The tune-measurement shaker has been used to establish coherent betatron oscillations of a specific beam bunch in one plane (horizontal or vertical) with a frequency near the natural tune of the accelerator. These oscillations are then sampled at each PU in each of 1024 turns. With suitable machine conditions, an essentially constant amplitude of a few millimeters is observed in the plane of excitation, while little oscillation is produced in the orthogonal plane (as shown in figure 2 for a typical PU).

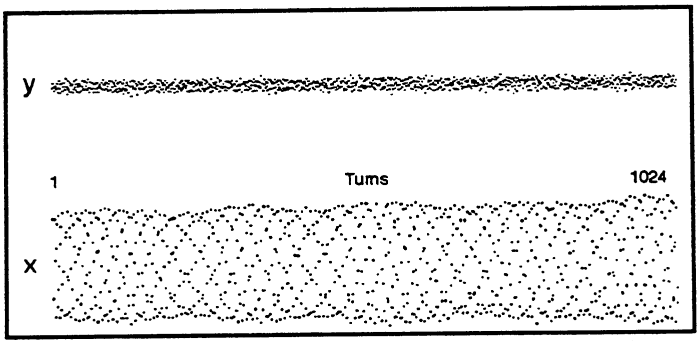

Fig. 2 : Single PU recording of excited horizontal beam motion (scale: 8 mm peak to peak, time= 88.9 µs/turn)

The observed oscillation in time at a given PU k can be described by the harmonic function :

$$x_k = A_k \cos(2\pi q_x f_{rev} t + \mu_k) \qquad (1)$$

where $A_k = K Z_k \sqrt{\beta_k}$ (2)

K is a constant for all PUs

Z_k is the relative scaling factor of PU k in hor. plane

A harmonic analysis is used to produce the best estimates of A_k and μ_k at each PU :

$$A_k = \frac{2\sqrt{(C^2 + S^2)}}{N} \qquad (3)$$

$$\mu_k = -\tan^{-1}\left(\frac{S}{C}\right) \qquad (4)$$

where $C = \sum_{m=1}^{N} x_{km} \cos(2m\pi q_x)$ (N=1024)

$$S = \sum_{m=1}^{N} x_{km} \sin(2m\pi q_x)$$

Figure 3 shows an example of the phase values obtained for a horizontal excitation of an e^+ bunch at the injection energy of 20 GeV. In the 8 arcs, the 60° lattice generates a regular pattern in the observed phases. For phases measured in this way the statistical error is 1° and there is no systematic error since the exact timing of the measurement is given by the bunch itself and the phases are independent of the individual PU calibration errors.

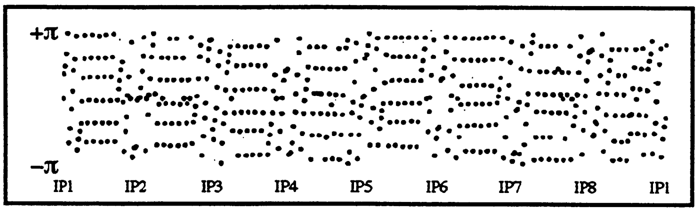

Fig. 3 : LEP betatron horizontal phase advance with 60° lattice, each point is a PU value.

The differences between the measured betatron phases, μ, and those calculated with the MAD model [8], μ_o, show a significant modulation at the 2nd harmonic of the betatron frequency due to the betatron beating effect. This can be expressed as

$$\mu(s) = \mu_o(s) + B(s)\sin[2\mu_o(s) + \theta(s)] + d(s) \qquad (5)$$

Except across the even IPs (those with the experiments), the functions $B(s)$, $\theta(s)$, and $d(s)$ are observed to vary slowly from PU to PU. Least squares fits were therefore made to equation (5) using the measurements from n PU's centred at each PU in turn, ensuring that no fits spanned the even IP's.

An example of the resulting smoothed functions (21 PU's per fit) obtained for the autumn 1991 LEP injection optics in the horizontal plane is shown in figure 4. The rise of 25.2° in $d(s)$ over the whole machine is due to the machine being operated at a different horizontal tune to that used for the MAD calculation. The discontinuities in $d(s)$ at each even IP result from real discrepancies in the low beta insertions of about 5%, while the undulations observed elsewhere are consistent with quadrupole gradient errors of a few 10^{-4}.

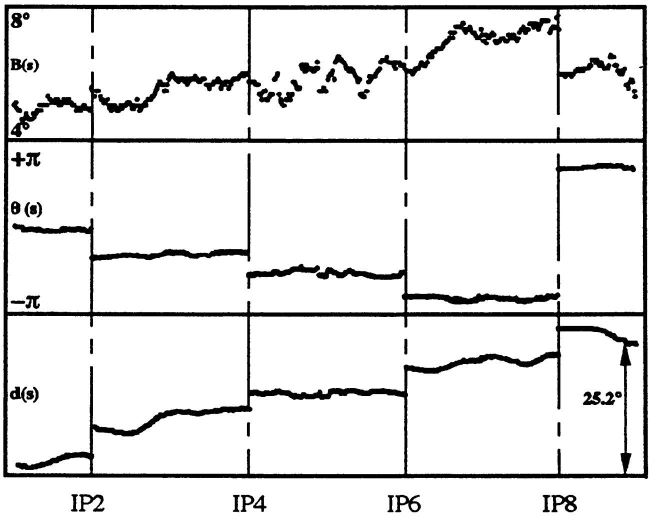

Fig. 4 : Example of the smoothed functions of s: B, θ and d.

Figure 5 shows a detail of the fits to the measured data in the half octants around IP8. The breaks in $B(s)$ and $d(s)$ are clearly visible. Whereas the 60° lattice produces a sampling of the phase advance modulation due to betatron beating every 120° in the arcs, the 90° lattice to be used in LEP in 1992 will reduce this sampling to every 180° in the arcs and only allow fitting of $B(s)$ in the straight sections.

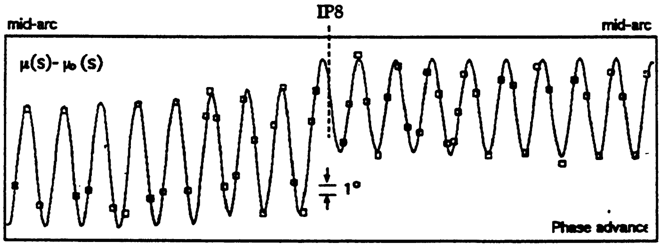

Fig. 5 : Details zoomed of the phase advance betatron beating around IP8.

Differentiating equation (5) with respect to s and ignoring the slow variation of $B(s)$, $\theta(s)$, and $d(s)$ with s, one obtains the following first order correction to the beta values from MAD, β_o :

$$\beta(s) = \frac{\beta_o(s)}{[1 + 2B(s)\cos(2\mu_o(s) + \theta(s))]} \qquad (6)$$

It is then possible to estimate the individual scaling factors for each PU in the plane being analysed using the measured amplitudes and equation (2). If the normalisation is chosen such that the average scaling factor for the WB PU's is 100%, then the factors for the NB PU's are distributed with a mean of 82% and sigma of 10%. These relative scaling errors are caused by the NB calibration procedure that uses electronic test pulses to simulate beam signals. This procedure is reliable and reproducible, but produces the wrong result mainly because the electronics do not have the same response to test pulses (1 ns) as they have to beam signals (100 ps).

It is planned to use the high precision values of beta obtained from the analysis described here to renormalize the PU scaling factors. However, as the PUs produce signals corresponding to diagonal positions on axes at 45° to the horizontal and vertical axes, both planes will have to be analysed and the effect of linear coupling in the machine taken into account. This work will be reported in a forthcoming paper [9].

The typical 20% error in the scaling factor has a limited effect on the closed orbit correction process, where it mainly affects the rate of convergence. However, it can have a significant effect on the measurement of spurious dispersion, especially in the presence of the large horizontal dispersion in the arcs.

3. ANALYSIS OF COHERENT SYNCHROTRON OSCILLATIONS

Dispersion in the horizontal and vertical planes has been measured by analysing coherent synchrotron oscillations induced with a phase modulation of the accelerating RF voltage. In one experiment [10], ϕ_s was modulated at a frequency of 974 Hz (corresponding to $q_s = 0.0867$) and oscillations up to $x = \pm 4$ mm were obtained for PU's in the arcs (where $D_x = 1.35$ m). A harmonic analysis at a frequency corresponding to q_s was applied to the measurements of these oscillations at each PU and a preliminary set of renormalised scaling factors applied to the amplitudes obtained.

In the horizontal plane, the expected shape of the dispersion function is obtained with maxima at Q17's and very low residual dispersion in the straight sections. When the average horizontal dispersion in the arcs is normalised to the expected value of 1.35 m, one obtains an rms value of $D_x = 5$ cm. in the straight sections. In addition, the effect predicted by Rugiero [11] that non vanishing dispersion in the RF cavities induces a betatron oscillation is particularly visible in the arcs around IP8 (see figure 6).

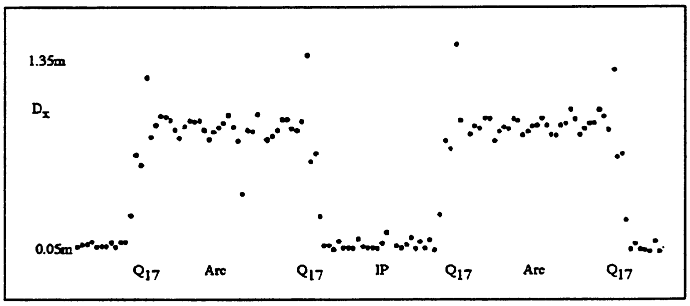

Figure 6. : Horizontal dispersion obtained from harmonic analysis of coherent synchrotron oscillations.

In the vertical plane, no regular pattern is observed in the amplitudes or phases. However, using the same normalisation as for the horizontal plane one obtains an the rms value of $D_y = 5$ cm in the straight sections and 16 cm in the arcs. It should be emphasized, however, that these measurements will only become reliable once the full renormalisation of the diagonal scaling factors referred to in the previous section has been completed.

Preliminary measurements done during a 90° optics MD [12] have indicated approximately half as much residual dispersion between IP2 and IP6 (the IPs with RF) as in the rest of the machine, but this measurement needs repeating in better conditions.

4. CONCLUSIONS

Thanks to its capability of simultaneous acquisition of single bunch positions at all PUs for a large number of turns, the BOM system has revealed itself as an outstanding tool for the study of machine optics. The precise modelling thus achieved allows for a PU calibration with proper beam signals. Further software development is expected soon to deliver these facilities to the operation crew. This sophisticated use of the instrument will bridge the gap until a second generation of NB electronics, now under development, allows more accurate measurements.

5. REFERENCES

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