RECENT ADVANCES IN THE MEASUREMENT OF CHROMATICITY VIA HEAD-TAIL PHASE SHIFT ANALYSIS

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Abstract

A so-called "Head-Tail" monitor has been operational in the CERN-SPS for a few years. The measurement of chromaticity using such a monitor relies on the periodic dephasing and rephasing that occurs between the head and tail of a single bunch for non-zero chromaticity. By measuring the turn-by-turn position data from two longitudinal positions in a bunch it is possible to extract the relative dephasing of the head and the tail, and so to determine the chromaticity. Until recently this technique had suffered from an unexplained "missing factor" when compared to conventional chromaticity measurements. This paper explains the source of this factor and also reports on the considerable experimental, simulation and analysis effort that has qualified the technique for use in the LHC.

INTRODUCTION

The determination of chromaticity by following the evolution of head-tail phase shifts after a transverse dipole excitation is a technique which does not rely on an accurate knowledge of the fractional part of the betatron tune and, for a machine operating well above transition, is virtually independent of beam energy.

Early experiments in the CERN-SPS [1] and at HERA-p (DESY) [2] have shown the feasibility of the technique for high-energy proton beams. More recent experiments [3] have highlighted several questions concerning the use of this technique for accurate chromaticity determination. The most important of these concerned a constant factor that appeared between the calculation of chromaticity via traditional techniques and that which was calculated from head-tail phase shift measurements. Here the source of this "missing factor" is explained and a method of correction is outlined. In addition this paper seeks to summarise the extensive theoretical work carried out on this technique [4] aimed at validating the robustness of the method for the LHC.

EXPLAINING THE "MISSING FACTOR"

A complete description of the detection and acquisition system can be found in [3]. A schematic of the layout can be seen in Fig. 1. All the results to date have shown discrepancies between the value of chromaticity measured via head-tail phase shifts and the traditional technique of tune tracking during energy modulation (referred to in the SPS as radial steering chromaticity measurements). A typical plot from such a comparison performed at the SPS is shown in Fig. 2. It can be seen that the head-tail results are consistently lower than the actual value, requiring a

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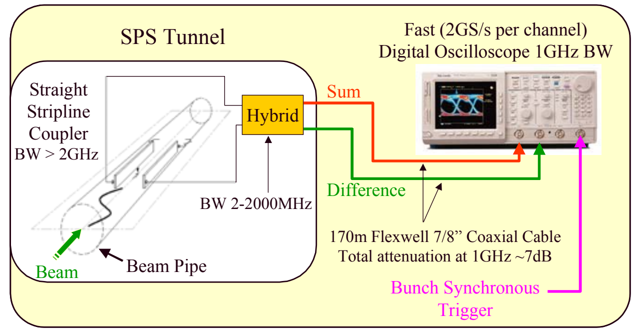


Figure 1. Schematic layout of the head-tail monitor in the CERN-SPS showing the various bandwidth limitations.

correction factor of 1.4, which remains essentially constant with chromaticity. The dotted line shows the trend of the head-tail measurements when corrected for this error, which is now seen to be in very good agreement with that measured using energy modulation.

In order to understand the origin of this correction factor, a more detailed study of both the underlying physics of the head-tail phase shift and the acquisition hardware associated with the head-tail monitor was initiated the results of which are presented in detail in [4].

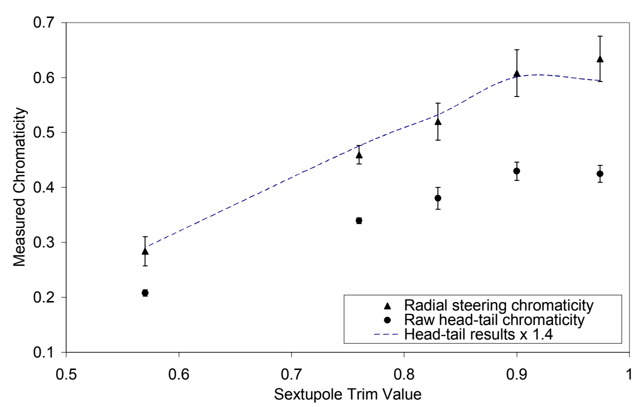


Figure 2. A comparison of head-tail and radial steering chromaticity, measured at 303GeV on the CERN-SPS.

These investigations showed that the source of the correction factor was the bandwidth limitations in the experimental set-up (indicated in Fig. 1). The main analogue contribution came from the 170m of cable connecting the hybrid in the SPS tunnel with the acquisition electronics. In addition, the 2 GS/s sampling rate of the oscilloscope reduces the upper frequencies that can be resolved without aliasing after digitisation to around 500 MHz. To see the effect that such bandwidth limitations have on the head-tail measurements, simulations were performed using PSpice with tracking data at input. The resulting chromaticity measurement was found to give a lower value than the original simulation, requiring a correction factor of ~ 1.3. This was close to the factor of 1.4 found in the real SPS data, and pointed to the cable bandwidth limitation as the main reason for the “missing factor”. A simulated delta signal where the head and tail are oscillating out of phase is shown in Fig. 3(a). Also plotted is the resulting signal after having passed through the coupler and cable for both 2 GS/s and 8 GS/s digitisation rates. The effect of the limitations in the bandwidth is clearly shown as an elongation of the original signal (the second, inverted pulse comes from the reflection due to the coupler pick-up).

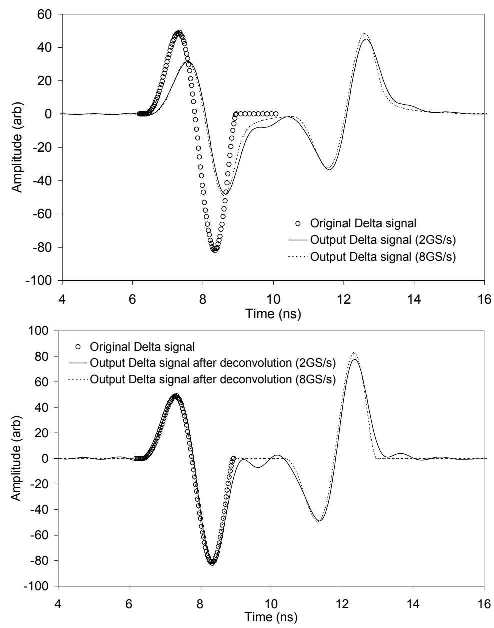


Figure 3. (a) The effect of cable bandwidth and sampling rate on an input delta signal. (b) The result of deconvolving the output signal with a known cable response for two different sampling rates.

On the basis of this evidence a deconvolution routine was added to the head-tail analysis program to take into account the attenuation and phase variations due to the cable. Fig. 3(b) shows the result of deconvolving the output signals shown in Fig. 3(a) with the known simulated cable response. For a sufficiently high sampling rate (8 GS/s in this case) it can be seen that the original signal is perfectly reproduced, as would be expected.

THE EFFECT OF ACCELERATION

Asymmetric Head-Tail Measurements on Accelerating Buckets

During acceleration, the deformation of the bunch alters the way in which the head and tail change phase. Calculations using a simple two particle model have shown that the phase change at the head of the bunch is reduced, while that at the tail is increased. This can be expressed in terms of a scaling factor with respect to the expected maximum phase difference ($\Delta\psi_{max,lin}$) obtained between any two slices in the bunch for a stationary bucket.

$$\Delta\psi_{\max}(\hat{\tau}) = S(\hat{\tau})\,\Delta\psi_{\max,lin}(\hat{\tau}) \qquad \textbf{(1)}$$

Fig. 4(a) shows the result of this for various synchronous phases of the RF when phase difference is calculated asymmetrically between the head and centre or centre and tail. It is clear from these results that an asymmetric measurement on an accelerating bucket can lead to large errors in the calculated chromaticity.

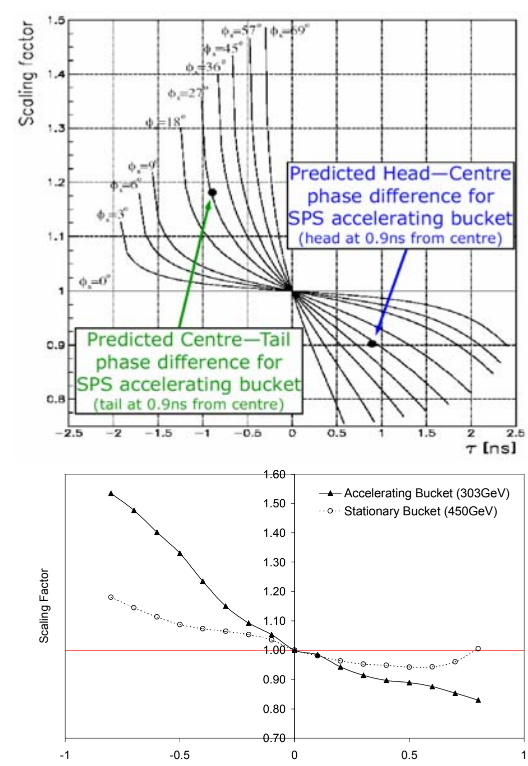


Figure 4. (a) Scaling factor S(τ) as defined in Eq. 1 for a 200 MHz RF system and different values of the synchronous phase. (b) Results from the SPS for an accelerating and stationary bucket.

The results of the simulations were compared to measurements taken at the SPS (Fig. 4(b)). In the case of the stationary bucket it can be seen that there is only a slight effect on the value of chromaticity even when the head or tail reach the extreme edges of the distribution, where the effects of non-linear synchrotron motion become important (which was not taken into account in the simulations). However, for the accelerating bucket there is a marked difference between measurements taken at the head of the bunch and those taken at the tail. A comparison with the simulations of Fig. 4(a) show a good agreement in the general trend of the scaling factor, with the measured factor being somewhat larger than that predicted.

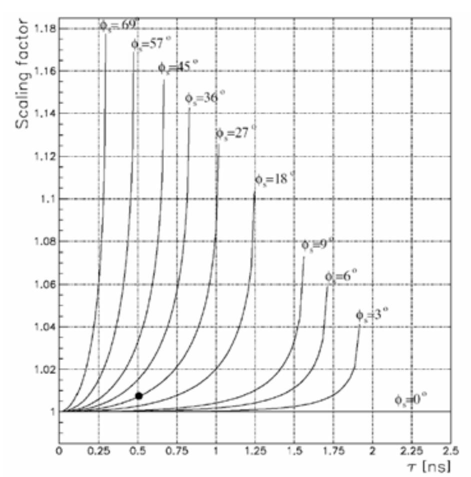
Symmetric Head-Tail Measurements on Accelerating Buckets

If one now considers symmetric head-tail measurements, i.e. calculating the phase difference between two positions located symmetrically about the bunch centre, then one obtains the results shown in Fig.5(a). Here the scaling factor $S_{sym}(\tau)$ is defined as:

$$S_{sym}(\tau) = [S(\tau) + S(-\tau)]/2 \qquad \textbf{(2)}$$

with $S(\tau)$ being the scaling factor defined in Eq 1. It can be seen that the error resulting from such symmetric measurements is very small for head/tail positions relatively close to the bunch centre.

The experimental results obtained from the SPS for a stationary and accelerating bucket are shown in Fig 5(b). For the stationary bucket there is no significant error up to head/tail positions of 0.6ns. After this the error increases, probably due to the residual imperfections and noise in the acquisition system. The general trend for the accelerating bucket is also in agreement with that obtained by calculation. However, for a reason which is not clearly understood, the overall scaling factor is found to be significantly larger than that predicted by the simulations.



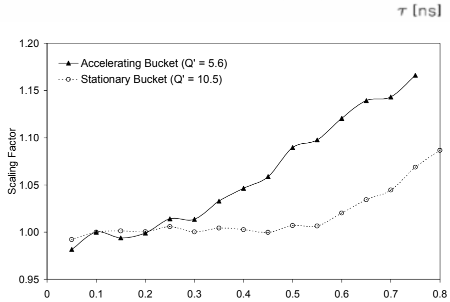


Figure 5. Scaling factor $S_{sym}(\tau)$ as defined in Eq. 2 for a 200 MHz RF system and different values of the synchronous phase.

CONCLUSIONS AND OUTLOOK FOR THE LHC

On the experimental side, both the method and acquired data is now much better understood. The addition of the deconvolution routine into the analysis algorithm to take account of cable attenuation has significantly reduced the "missing factor" between the head-tail and traditional chromaticity measurements.

In agreement with the simulations, it has been experimentally verified that the method is applicable both for stationary and accelerating buckets with the constraint that the measurement is performed close to and symmetrically about the bunch centre.

In addition, dedicated calculations have been performed for the LHC to take into account other possible causes of perturbation. Simulations of the effects of second and third order chromaticity show that even for the most pessimistic case the error introduced is less than 0.2 units of chromaticity. A 20% off momentum beta-beating and linear coupling (if arc-by-arc compensated as foreseen in the LHC) have also been shown to give very little perturbation to the measurement. Finally, an extrapolation of SPS data taken at 26 GeV seems to indicate that, at nominal current, the accuracy of the head-tail chromaticity technique should practically not be affected by the transverse impedance of the LHC ring.

For the future, a new system working with sampling rates of up to 10 GS/s will be installed in the SPS. It is hoped that this increase in the sampling rate along with the continued deconvolution of the cable response will completely eliminate the residual "missing factor". In addition, closed orbit compensation electronics will be added to improve the sensitivity of the acquisition and allow the measurement to be made with much smaller excitation amplitudes.

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