CHROMATICITY MEASUREMENTS AT HERA-P USING THE HEAD-TAIL TECHNIQUE WITH CHIRP EXCITATION

A. Boudsko, TRIUMF, Vancouver, Canada
O. R. Jones, H. Schmickler, CERN, Geneva, Switzerland
M. Wendt, F. Willeke, DESY, Hamburg, Germany

Abstract

Experiments have been performed in the HERA proton ring (HERA-p) to test a quasi non-destructive method of chromaticity measurements for protons. The method is based on the detection of the head-tail phase shift of coherend betatron oscillations using a broadband beam position pickup and a commercial "fast-frame" oscilloscope. Previous experiments have relied on a single kick for transverse excitation, whereas the results presented here were carried out using swept frequency "chirp" excitation. The tests proved to be successful, and the method seems to be a good candidate for chromaticity measurement in new large hadron accelerators, such as LHC.

1 INTRODUCTION

In any superconducting accelerator the control of *chromaticity* during machine transitions like energy ramping or beta squeezing is of paramount importance. The classical method of chromaticity determination, i.e. measurements of the betatron tunes for different settings of the beam momentum, is in this case only of limited use. In this paper we describe the results of applying the so-called *head-tail* chromaticity measurement [1] to the beams in HERA-p. This method relies on the fact that for non-zero chromaticity a dephasing/rephasing of the betatron oscillations occurs between the head and the tail of a bunch during synchrotron oscillations. After transverse excitation, the measurement of the turn-by-turn position of two longitudinal positions in a bunch allows the relative phases to be extracted and the chromaticity to be calculated.

In contrast to the results reported in previous publications [1, 2] which used a single kick for beam excitation, the data in this report is obtained by *resonant chirp beam excitation*. Altough the primary motivation for using this technique in HERA-p is the lack of a sufficiently strong deflection kicker in the vertical plane, the results are of general interest.

2 THE HEAD-TAIL PRINCIPLE

Assuming longitudinal stability, a single particle will rotate in longitudinal phase-space at a frequency equal to the synchrotron frequency. During this longitudinal motion the particle also undergoes transverse motion, which can be described by the change in the betatron phase, $\Theta(t)$, along the synchrotron orbit. If the whole bunch is kicked transversely, then the resulting transverse oscillations for a given longitudinal position within the bunch can be shown [1] to be given by

$$y(n) = A\cos\left[2\pi n Q_0 + \omega_\xi\,\hat{\tau}\left(\cos\left(2\pi n Q_s\right)-1\right)\right] \quad (1)$$

where n is the number of turns since the kick, Q_0 is the betatron tune, Q_s is the synchrotron tune, $\hat{\tau}$ is the longitudinal position with respect to the centre of the bunch, and ω_ξ is the chromatic frequency and is given by

$$\omega_\xi = Q'\,\omega_0\frac{1}{\eta} \quad (2)$$

Here Q' is the chromaticity, ω_0 is the revolution frequency and $\eta = 1/\gamma^2 - 1/\gamma_{tr}^2$. If we now consider the evolution of two longitudinal positions within a single bunch separated in time by $\Delta\tau$, then from (1) it follows that the phase difference in the transverse oscillation of these two positions is given by

$$\Delta\Psi(n) = -\omega_\xi\,\Delta\tau\left(\cos\left(2\pi n Q_s\right)-1\right) \quad (3)$$

This phase difference is a maximum when $nQ_s \approx 1/2$, i.e. after half a synchrotron period, giving

$$\Delta\Psi_{\max} = -2\,\omega_\xi\,\Delta\tau \quad (4)$$

The chromaticity can therefore be written as

$$\begin{aligned} Q' &= \frac{-\eta\,\Delta\Psi(n)}{\omega_0\,\Delta\tau\left(\cos\left(2\pi n Q_s\right)-1\right)} \\ Q' &= \frac{\eta\,\Delta\Psi_{\max}}{2\,\omega_0\,\Delta\tau} \end{aligned} \quad (5)$$

3 EXPERIMENTAL PROCEDURE

3.1 Hardware Setup

Fig. 1 shows the hardware setup. The transverse displacement signal of the proton beam was detected with the two horizontal 40 cm long stripline-like electrodes of a broadband beam position pickup ($\beta \approx 33$ m) [1]. Their signals were adjusted in time with a variable delay-line and combined in a Δ/Σ-hybrid (*M/A COM*, model H-9). Additional fixed and variable attenuators were used to minimize the common mode signal due to the static beam displacement, i.e. the transverse beam orbit. Both output signals of the hybrid, Δ (displacement) and Σ (intensity), were acquired using a *Tektronix* 784C digital oscilloscope (1 GHz analogue

[1] slotted coaxial electrodes, usable bandwidth $\approx$ 4 GHz

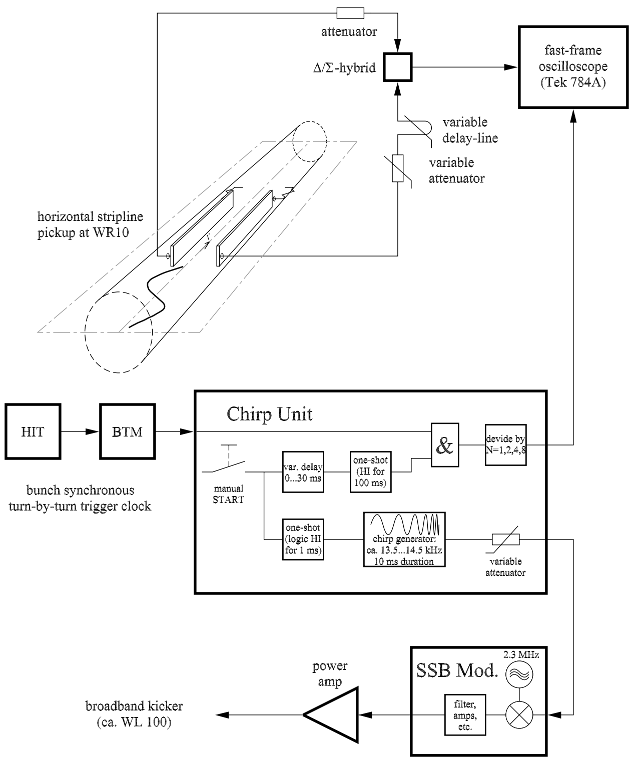

Figure 1: Hardware setup for the chromaticity measurements with chirp excitation.

bandwidth, 4 GS/s single channel sampling rate). The Σ signal was used in the off-line analysis to reduce the effect of jitter in the trigger signals. The necessity of this second signal channel limited the sampling rate to 2 GS/s. The oscilloscope was set to "fast-frame" mode, which allowed the capture of signals for up to 372 consecutive turns [2]. Each "frame" covered 25ns, with 50 sample points spaced by 500 ps, giving the displacement vs. time of a single bunch.

The chirp excitation was started manually. This opened a 100 ms gate that passed bunch-synchronous turn-by-turn triggers to the oscilloscope. This signal was provided by the *HERA Intergrated Timing* (HIT) system. The chirp duration and its lower and upper frequencies were programmed by varying R-C combinations. The output signal was added to the SSB modulator of the resonant excitation kicker of the betatron tune measurement system.

The oscilloscope was PC-controlled via GPIB. A HP-VEE program dumped the data of all 372 frames automatically into an Excel spreadsheet and stored it with a timestamp. The PC was also used for a brief off-line analysis of the data.

3.2 Measurements

The experiments were carried out during 5 shifts on the weekend 12/13 December, 1998 [3].

After establishing a sufficient chirp excitation *amplitude*, *frequency range* (13.5. . .14.5 kHz ≡ 0.285. . .0.31 tune) and *duration* (10 ms ≡ 500 turns) the method was tested by staying at the 40 GeV proton injection energy of HERA-p. Starting with 10 freshly injected bunches (≈ 5 mA beam current) 3 chirp measurements per sextupole setting were carried out and compared with the classical rf-variation/tune-detection method. The sextupoles were varied to give 7 different chromaticity settings in the range of -10. . .+10 units. No beam breakup or losses were observed at this energy, but a reduced proton lifetime was noticed during the chirp excitation.

Further measurements, again using 10 bunches, were carried out at the start of each ramp file (at 70, 150 and 300 GeV), as well as during the ramp. A chirp measurement above 300 GeV proved to be difficult to achieved, due to the weak excitation level at this energy, and the tendency of the beam to get unstable for negative chromaticities.

4 DATA ANALYSIS

Since the sampling clock of the digital oscilloscope used in these experiments could not be synchronised to the turn-by-turn bunch trigger, it was necessary to sample both, the Σ and Δ signals from the hybrid coupler. The Σ signal was then used to re-align each frame and hence correct for this jitter. This frame-by-frame correction factor was then applied to the Δ signal before starting the analysis. The head and tail analysis times were chosen so as to be symmetrical about the bunch centre. The transverse positions at these times in the bunch were estimated by linear interpolation of the two nearest sampling points. Having obtained a set of head and tail data, phase demodulation using Hilbert transformation was carried out to obtain the turn-by-turn head and tail phase relative to a reference frequency. This reference frequency was chosen to be the average betatron frequency calculated from the Fourier power spectrum of both the head and tail data. The choice of reference frequency is however not critical, since we are ultimately only interested in the phase difference between the head and tail oscillations. The chromaticity was calculated by applying Equation (5) directly to the phase difference between the head and tail.

5 RESULTS

Figure 2 shows the typical response of the head and tail of a bunch to chirp excitation. This is characterised by a growing oscillation amplitude followed by an amplitude "beating" for which the depth of the trough is a function of the width of the betatron tune peak and the rate at which the chirp is swept across the betatron resonance. The quoted head and tail timing is always relative to the centre of the bunch. The dependence of the phase evolution on different longitudinal positions in the head and tail of the bunch is shown in Figure 3. Here the swept "chirp" frequency crosses the betatron frequency at around turn 50, from which time the head and tail phases start to diverge from each other. What is also visible is that the response

[2] or the 2nd, 4th or 8th multiple by trigger division

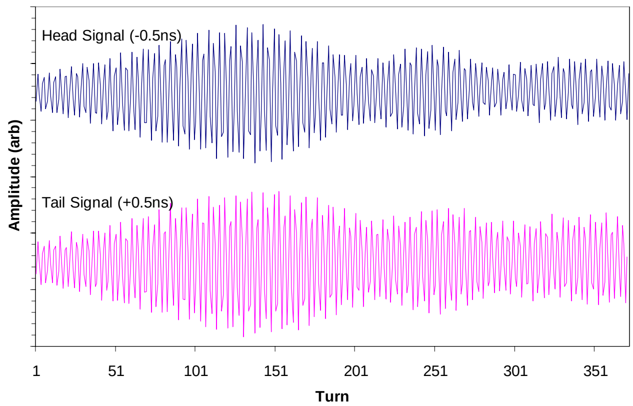

Figure 2: Transverse signals from the head and tail of a bunch after chirp excitation (70 GeV, horizontal chromaticity = +4).

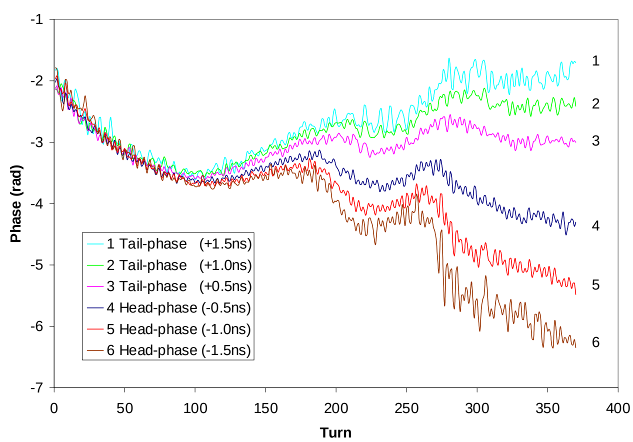

Figure 3: Phase evolution of several longitudinal positions within the same bunch relative to the centre of the bunch (70 GeV, horizontal chromaticity = +4).

of the bunch to the chirp itself produces a perturbation in the phase evolution. This proved to be a problem for certain chromaticities, where the troughs seen in Figure 2 went down to virtually zero, leading to large phase pertubations.

Figure 4 is the result of applying Equation (5) to the phase differences of the head and tail phases shown in Figure 3. By averaging the perturbations caused by the chirp, the resulting chromaticity is seen to lie between +3 and +5 units, which compares quite well with the +3 units measured using the classical method in the control room.

Figure 5 shows the result of two measurements performed at 300 GeV for positive and negative chromaticity. Again we see that the calculated chromaticities agree very well with the values measured classically.

6 CONCLUSIONS

The results presented demonstrate the possibility of mesuring chromaticity using chirp excitation in less than 1000 turns, at energies up to 300 GeV. The main advantage of this technique over the current chromaticity measurement in HERA-p is that it can be performed during the energy

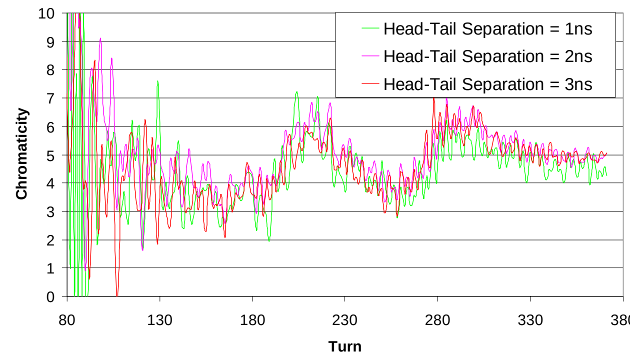

Figure 4: Turn-by-turn chromaticity for three different head-tail separations (70 GeV, hor. chromaticity = +4).

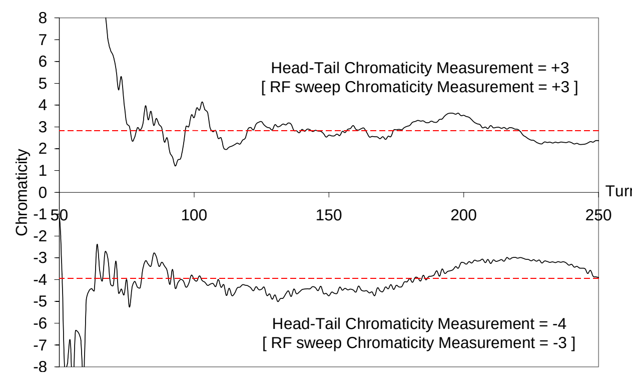

Figure 5: Turn-by-turn chromaticity for positive and negative chromaticity at 300 GeV (± 1 ns head-tail separation).

ramp. Since only 15 % of the total available kick strength was used in obtaining these results, measurements at higher energies could be made possible simply by increasing the strength of the chirp signal. A beam break-up tendency during chirp excitation was observed at higher energies ($>$300 GeV), but only for negative chromaticity.

Errors in the measured chromaticity were mainly due to the phase perturbations introduced by the chirp itself, and the fact that the chirp was not synchronized to the data acquisition. The latter meant that the turn at which the chirp crossed the betatron frequency had to be estimated by eye from the phase evolution plots, which could lead to errors of up to ± 2 units in the calculation of chromaticity. Synchronising the chirp to the acquisition would allow the resonant tune to be calculated from the measured betatron tune and a knowledge of the chirp parameters.

7 REFERENCES

[1] D. Cocq, O. R. Jones, H. Schmickler, "The Measurement of Chromaticity via a Head-Tail Phase Shift", 8th Beam Instrumentation Workshop BIW '98, Stanford, CA, USA; 4 - 7 May 1998.

[2] O. R. Jones, H. Schmickler, M. Wendt, F. Willeke, "HEAD-TAIL Chromaticity Measurements at HERA-P (9/7/1998)", CERN Internal Note, SL Division, 29/7/98.

[3] logbook HERA-"E"u."P"-XXXIV, pp. 129-132.