ANALYSIS OF MULTI-TURN BEAM POSITION MEASUREMENTS IN THE CERN PS

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Abstract

The observation of betatron oscillations following a deflection by a kicker pulse offers the possibility to study various machine parameters. The decoherence and recoherence of a bunch's centre-of-charge signal, for example, is governed by chromaticity, momentum spread and transverse nonlinearities. The multi-turn acquisition system of the CERN PS is able to store the beam position information of about 2000 turns. A careful analysis of such data can be used to extract estimates of the parameters involved, as well as to reconstruct the beam dynamics in phase space. Experimental results are compared to existing models.

1 INTRODUCTION

In the framework of a project to improve the efficiency of the high intensity beams in the CERN Proton Synchrotron (PS) machine [1] by increasing the number of accelerated protons and decreasing the number of lost particles, a new extraction scheme has been developed [2] to replace the standard Continuous Transfer (CT) [3]. This scheme is based on adiabatic trapping of charged particles inside stable islands in phase space generated by sextupoles and octupoles, so as to significantly reduce the losses on the electrostatic septum at extraction and improve the quality of the extracted beam [4]. As the main ingredient for this new type of extraction is the topology of the phase space, tools for phase space reconstruction, based on multi-turn beam position measurements, are mandatory for any test of the proposed extraction. A new multi-turn acquisition system and interactive analysis toolkit have been developed to perform first measurements [5, 6]. In this paper, we present measurements made with the new system. Results of the analysis are compared to model calculations.

2 MEASUREMENTS AND RESULTS

2.1 De- and Re-coherence

Transverse betatron oscillations around the closed orbit, induced by a single deflection with a transverse kicker, are observed with electrostatic pick-ups. Hence, only the centroid motion of the proton beam is detected. For zero tune spread, the motion of the centre-of-charge would represent single particle dynamics and be harmonic. For a realistic beam, a tune spread is present and the centre-of-charge signal will decohere with time. The initially localised phase space distribution of the bunch will, given enough time, form an annulus. The pick-up signal will correspondingly show a diminished oscillation amplitude. Modulated with the synchrotron frequency, a recoherence of the signal can be observed, equivalent to a re-localisation in phase space (see Fig. 1). Two main sources of tune spread have to be taken into account: energy spread and nonlinear detuning. The first induces tune spread through a non-zero chromaticity, while the latter generates a tune spread related to the particles' amplitude. According to [9] the effective centroid motion is described by

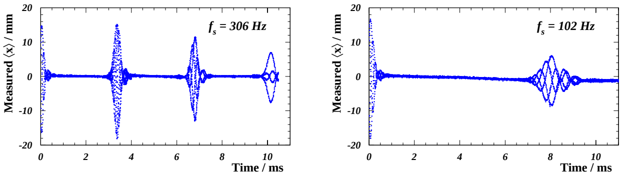

Figure 1: Measurements of de- and recoherence for two synchrotron frequencies. Both plots are composed of several individual datasets with measurements started at different times after the kick (the current setup only allows the acquisition of about 2000 turns).

$$\langle X\rangle(t) = \sqrt{\beta\varepsilon}\, A_s(t)\, A(t) \cos\left(2\pi\nu_0 t + \Delta\langle\phi\rangle(t)\right). \qquad (1)$$

A and A_s are decoherence factors defined as

$$\begin{aligned} A_s(t) &= e^{-\frac{\alpha^2}{2}} \qquad \alpha = \frac{2\sigma_s Q'}{\nu_s}\sin\left(\pi\nu_s t\right) \\ A(t) &= \frac{1}{1+\theta^2}\exp\left[-\frac{Z^2}{2}\frac{\theta^2}{1+\theta^2}\right] \\ \Delta\langle\phi\rangle(t) &= -\frac{Z^2}{2}\frac{\theta}{1+\theta^2} - 2\arctan\theta \end{aligned}$$

with t the turn number and Z the kick amplitude in units of the rms beam size. The parameter $\theta = 4\mu t$ describes the time dependence of the decoherence, and $-\mu a^2$ is the tune shift with amplitude for a normalised amplitude a. With an energy spread and synchrotron tune known from other measurements, this offers the opportunity to extract the detuning parameter μ and the chromaticity Q' from a fit to the data.

As predicted by the model, Fig. 1 clearly shows the recoherence after one synchrotron period. The width of the second appearance of the signal is determined by the product of chromaticity and energy spread. For a dataset acquired during the campaign of phase space exploration, the chromaticity $\xi = Q'_x/Q_x$ could be determined as follos. The momentum spread was measured to be $\Delta p/p = 2\times10^{-3}$ and used as input parameter. A second input parameter is the horizontal tune, $Q_x = 6.243$, which was determined from the first 100 turns, before the signal amplitude has completely vanished due to decoherence. The chromaticity is then derived from a χ^2 fit of the model (1) to the measured data. The "statistical" uncertainty is obtained from the fit result and is scaled for a χ^2 per degree of freedom of one. A systematic uncertainty due to momentum spread of $\Delta\xi_{\Delta p/p} = \pm$ 0.05 can be estimated by the spread of resulting chromaticity for different $\Delta p/p$. The result, obtained for a kicker deflection of 0.93 mrad is $\xi = (0.225 \pm 0.007 \pm 0.050)$. The same fit also gives a synchrotron tune of 0.00060, which is in reasonable agreement with the value from an independent measurement. The factor describing the nonlinearity, μ, is found to be 6×10^{-7}. Although the derived chromaticity is of the expected order, the agreement between data and model is far from perfect. In the measurement there is, for example, a small reappearance of the signal immediately after the first decoherence (see Fig. 1) that is unexplained. In addition, the height of the second main signal is not reproduced correctly which seems to indicate a problem in the modelling of the nonlinearity.

2.2 Phase Advance

To verify the model of the PS, measurements and simulations of the horizontal phase advance have been performed for several different situations: the bare machine, with different extraction bumps switched on, with a kick enhancement quadrupole on and with everything switched on at the same time. The phase advance between two beam position monitors was derived from an FFT of the oscillation observed at these two monitors after a weak kick. These measurements are displayed in Fig. 2, where the phase advance in units of 2π is shown as function of the section in which the second pick-up is located. The start phase is taken from MAD. The plot on the right shows the relative difference in phase advance between measurement and machine model. The agreement between simulation and measurement appears to be reasonable.

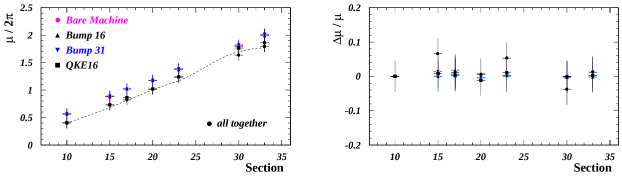

Figure 2: Measurements of the phase advance between two pick-ups versus section in which the second of the two pick-ups is located. The start phase is taken from MAD (left). Relative error in phase advance between measurement and model (right).

2.3 Islands

In order to detect islands in the transverse phase space, created by the available nonlinear elements present in the PS machine, the kicker strength was varied between 0.65 and 1.12 mrad in steps of 0.09 mrad. The sextupoles normally used for slow extraction as well as the octupoles used to stabilise beam instabilities were powered to generate stable islands. The computed phase space map is shown in Fig. 3 in normalised coordinates at the beam position monitor used for the measurement. Two resonant regions are clearly visible: the inner one shows four stable islands, while the outer one five. The islands related with the fourth-order resonance have an acceptance of about (2.5 ± 0.1) μm each [10]. During the experimental sessions, only the inner part of the phase space up to forth-order resonance was probed. For a case of partial capture, particle motion outside the resonance islands will de-cohere whereas particles inside the resonant phase space regions will only filament within the island boundaries. The corresponding horizontal distribution after decoherence can be viewed as a superposition of an annular distribution and a localised distribution in the island. It is possible to show that the mean of such a distribution can be expressed as [10]

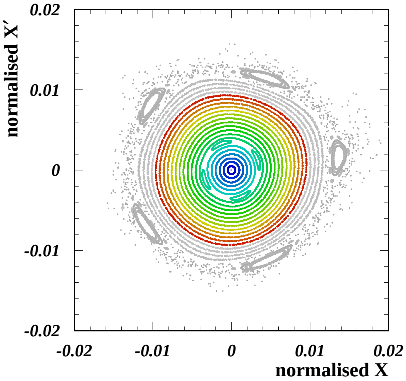

Figure 3: Horizontal phase space generated with MAD at the pick-up in section 10. Two chains of stable islands (period 4 and 5) are clearly visible. The inner chain is the one studied during the measurement sessions.

$$\tilde{\mu}(z) \;=\; \frac{\mu_I}{1+\frac{1}{z}}$$

where μ_I denotes the island position and z the ratio of particle numbers inside and outside the island. With the theoretical island position extracted from the machine model, for example with the method of iterative elimination [10], the capture efficiency z can easily be calculated. A rough estimate of z can also be obtained from the ratio of the first-turn amplitude to the amplitude after filamentation has occurred. However, great care has to be taken, since the first-turn amplitude will reflect the centre-of-charge of the bunch rather than the island position. The error of this assumption is negligible only if 100 % of the beam is captured. Even in this case, there is still an uncertainty that can arise from a filamentation process inside the island (see [10] for a detailed discussion).

One measurement dataset for a kicker strength of 1.03 mrad is displayed in Fig. 4. The fast decoherence due to the combined effect of chromaticity and nonlinearities is again clearly visible. From this measurement, the mean position of the particle distribution $\tilde{\mu}(z)$ in the fourth-order resonance islands (shown in Fig. 4) is estimated to

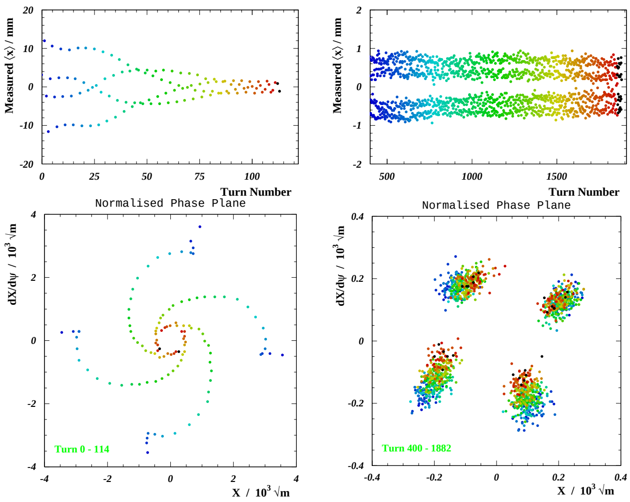

Figure 4: Upper part: Horizontal beam position vs. time measured with a pick-up for the few turns right after the kick (left) and for the last 1500 turns (right). Bottom part: Normalised phase space reconstructed from two pick-ups.

be 0.6 mm, while the corresponding island position in the phase space portrait of Fig. 3 is 10.3 mm. Hence, the capture efficiency could be estimated to be about 6 %.

2.4 *Tune Shift and Kick Amplitude*

For the whole set of measurements done with the settings described in section 2.3, the change in tune as function of amplitude was extracted. Figure 5 shows the tune determined with Lomb Normalised Periodogram (LNP) [8] from the first turns where decoherence is not yet complete, as function of the quantity $W = a^2/\beta$, where β is the value of the horizontal beta-function at section 10 and a the maximum oscillation amplitude. The amplitude-dependence is clearly visible. For a comparison with model calculations carried out with the MAD program, however, a better understanding of the nonlinearities involved is mandatory. The measured horizontal tune and the tune obtained by MAD tracking shows a significant difference: $Q_x^{\mathrm{meas}} = 6.249$ and $Q_x^{\mathrm{MAD}} = 6.230$. A possible source of such a difference could be found in closed orbit distortion inside nonlinear elements. An offset of the order of 10 mm could account for the necessary tune shift. If the linear tune of the machine is properly adjusted in the MAD model, the resulting detuning curve (triangles in Fig. 5) the experimental data fits quite well.

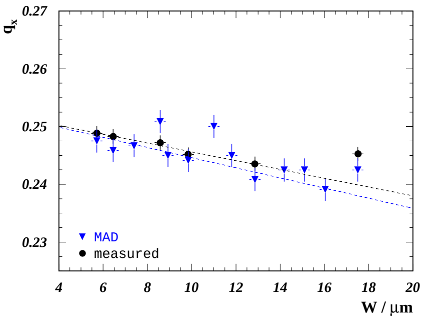

Figure 5: Tune determined with LNP from the first turns where decoherence is not yet complete, as function of $W = a^2/\beta$. The error bars represent a rough estimate of the uncertainty on the tune computation.

3 SUMMARY AND OUTLOOK

The observation of betatron oscillations following a deflection by a kicker pulse offers the possibility to study various machine parameters. During the year 2001 run, first measurements were made with the new PS multi-turn acquisition system based on a fast digitiser and an interactive analysis toolkit. The phase advance was determined for different machine settings, decoherence and recoherence of the beam centroid signal after an excitation with a kick was studied, and the tune shift was measured as function of kick amplitude. Furthermore, the transverse phase space topology was probed to detect resonance islands and investigate capture efficiency.

During the forthcoming measurement campaign, the core activity will be phase space reconstruction. Such a technique will be the key tool to allow realistic tests of the proposed extraction technique based on island capture. For this, sextupoles and octupoles have been installed in the PS ring to perform preliminary tests of the new extraction [11].

4 ACKNOWLEDGEMENTS

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