NON-LINEAR BEAM DYNAMICS TESTS AT THE CERN PS IN THE FRAMEWORK OF THE MULTI-TURN EXTRACTION

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Abstract

In the framework of the CERN PS Multi-Turn Extraction several campaigns of measurements probing the non-linear beam dynamics have been carried out. These measurements range from measurement of non-linear chromaticity to phase space portraits, de-coherence and re-coherence measurements, secondary island tune etc. In this paper these measurements will be reviewed and the results presented and discussed in details.

INTRODUCTION

In recent years a novel approach to perform multi-turn extraction (MTE) from a circular particle accelerator has been proposed, which is based on beam trapping in stable islands of horizontal phase space [1]. Following a period of experimental verification it was decided to implement it in the CERN Proton Synchrotron (PS) to replace the so-called Continuous Transfer (CT) extraction method that is based on beam shaving onto an electrostatic septum. This type of beam is used for the Fixed Target (FT) physics program at SPS and for the neutrino production for the CNGS. During the MTE process the beam is transversally divided into four beamlets around a remaining beam core. In the framework of MTE optimisation process, several campaigns of measurements probing the non-linear beam dynamics have been carried out (non-linear chromaticity, detuning with amplitude, secondary islands' tune). All these measurements, applied to the beamlets and core are presented in this paper and discussed. The errors quoted in the following analysis are either derived from averages of several measurements or from the errors related with the fit procedures. The main parameters of the single bunch beam used for MTE studies are listed in Table 1.

Table 1: MTE Test Beam Characteristics

Beam momentum	14 GeV/c
Intensity	1×10^{10} p/b
Trans. norm. emittance (H/V) RMS	1 μm
RMS Longitudinal emittance	0.29 eVs
RMS Δp/p	0.31×10^{-3}
RMS bunch length	21.2 ns
Synchrotron frequency	220 Hz

MEASUREMENTS FOR THE CORE

When a beam is transversely kicked, betatron oscillations are induced. Due to the intrinsic betatron frequency spread of the beam, the beam filaments in the corresponding transverse phase space to occupy an annulus. As a result of that the oscillations of the centroid of the transverse positions of the beam particles measured by a pick-up decay. Such a de-coherence is mainly due to two sources of particles phase spread: transverse non-linearities coming from the machine and chromaticity which couples the betatron phase of the beam with its energy spread. In the absence of non-linearities the signal given by the centroid beam position in a pick-up will de-cohere and then re-cohere with a periodicity of a synchrotron period. The maximum amplitude of the re-coherence peaks is damped by the non-linearities after each synchrotron period.

Orbits of the MTE test beam have been measured when such transverse kicks of various amplitudes are applied. One example of measured orbit is shown in Fig. 1 (top), corresponding to an initial kick amplitude of around 4.5 mm. Re-coherence peaks are clearly visible, separated by around 2250 turns corresponding to a synchrotron frequency of 220 Hz, in agreement with the PS longitudinal parameters. The centroid motion has been extracted from these measurements and fitted by a combination of chromaticity and detuning effects as, according to Refs. [2, 3, 4] one can model the centroid motion $\bar{x}(N)$ as

$$\bar{x}(N) = \sqrt{\beta\epsilon} A_s(N) A(N) \cos\left[2\pi\nu_0 N + \Delta\bar{\phi}(N)\right] \quad (1)$$

with

$$A_s(N) = e^{-\alpha^2/2} \quad (2)$$

$$A(N) = \frac{1}{1+(Q_p N)^2} \exp\left[-\frac{1}{2}\frac{(Q_g N)^2}{1+(Q_p N)^2}\right] \quad (3)$$

and

$$\alpha = 2\sigma_s Q' \nu_s^{-1} \sin \pi\nu_s N,\ Q_p = 4\pi\mu,\ Q_g = Z Q_p, \quad (4)$$

where ν_s, ν_0, σ_s are the synchrotron tune, the transverse tune and the RMS relative energy spread, respectively; μ is the detuning for amplitudes measured in units of σ_x, and $Z = \beta\Delta x'/\sigma_x$ is the transverse kick imparted to the bunch.

All these measurements and analyses have been performed for different kick amplitudes. One example of extracted centroid envelope, corresponding to the kick amplitude of 4.5 mm fitted by the de-coherence formulae is shown in Fig. 1 (bottom). Figs. 2 and 3 show the chromaticity and detuning values extracted from the fits done for various kick amplitudes. Results from the fit have been compared to those given by the non-linear model of the PS [5]. Such a model has been obtained by fitting the non-linear chromaticity measurements with virtual non-linear kicks inserted in the 100 PS main combined function dipoles. The measured non-linear chromaticities used to fit the PS

ISBN 978-3-95450-115-1

Table 2: Non-Linear Chromaticity Measurement Results Used for Building the PS Main Model

	Q'	Q"
H	3.53 ± 0.03	-363 ± 8
V	2.06 ± 0.01	337 ± 3

model are given in Table 2. The results extracted from the fit of the beam centroid dynamics are in agreement as far as Q' is concerned (see Fig. 2), but a discrepancy of about a factor of two appears for detuning with amplitude (see Fig. 3). It is worth noting that after around 10000 turns

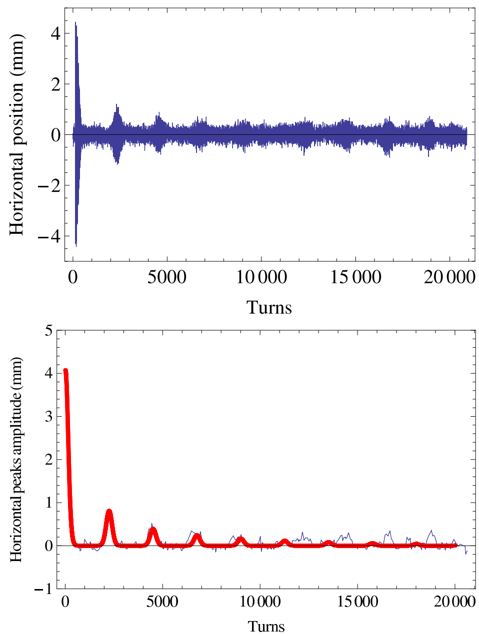

Figure 1: (Top) Measured beam centroid during 20000 PS turns and for an initial kick of around 4.5 mm. (Bottom) Beam centroid envelope (blue) and its corresponding fit (red). The pick-up used is the one in section 3.

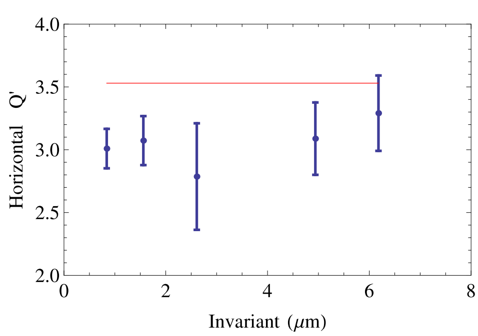

Figure 2: Horizontal chromaticity extracted from the fit as a function of the kicker strength (blue) and the corresponding value given by the model (red).

a new series of peaks appears in the centroid motion (see Fig. 1 - bottom). These peaks are still separated by a synchrotron period, but are time-shifted by about 1000 turns with respect of the series of peaks generated with the initial kick. It is also worth stressing that this secondary series of peaks is not fully reproducible and tends to be present in the measurements performed with the lower kick amplitude, rather than in those with larger kicks. For the time being no satisfactory explanation was found to this observation. An additional cross-check of the detuning measure-

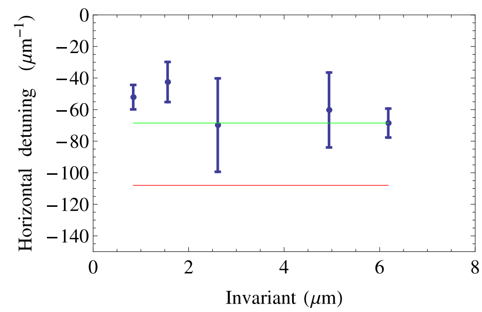

Figure 3: Horizontal detuning with amplitude extracted from the fit as a function of the kick amplitude (blue), corresponding value given by the model (red), and direct measurement of the detuning with amplitude (green).

ment was carried out by extracting the information from the tune from the time series immediately after the initial kick. For about 200 turns, the signal from the pick-ups is strong enough to ensure a good reconstruction of the horizontal tune. Therefore, it is possible to derive the detuning with amplitude from its very definition. The results are presented on Fig 4. The slope of the linear fit gives a detuning of $-68.5\,\mu\text{m}^{-1}$, which is in very good agreement with the results obtained from the fits of the centroid motion (see Fig 3). In the framework of the tests for alternative extrac-

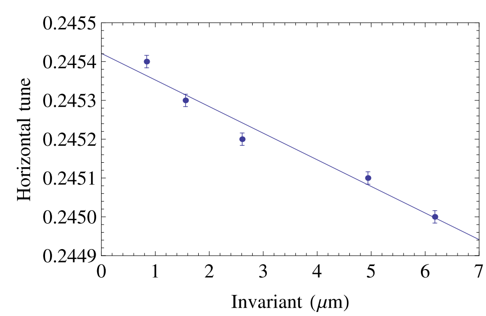

Figure 4: Horizontal tune as a function of the kick amplitude together with the corresponding linear fit. The tune was measured from the first turns after kicking the beam at different amplitudes. The slope is $-68.5\,\mu\text{m}^{-1}$.

tion schemes for the MTE [6] a special extraction bump was computed and tested with beam. For the MTE gymnastics it is essential that the optical parameters (tunes and chromaticities) are kept constant as possible. To verify this point, special measurements were performed and the beam excited during the rise of the bump, thus enabling tunes measurement, but also chromaticities fits from the centroid motion data. The results are presented in Fig. 5, where a clear variation of the horizontal chromaticity is visible. The contribution to this effect from the optics change during the bump rise time and the possible feed-down from the strong octupolar component of the PS main dipoles in the bump region will need to be estimated.

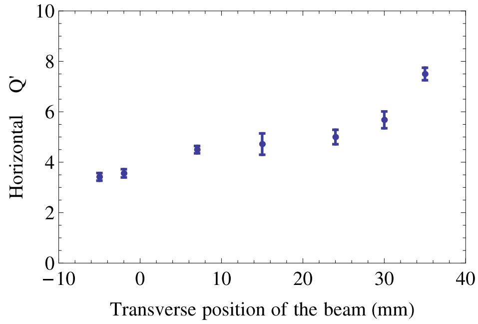

Figure 5: Horizontal chromaticity for different transverse beam positions during the rise of the special extraction bump. The pick-up the provided the data for the analysis and the beam position vs. time is the one in section 15.

NON-LINEAR EFFECTS IN ISLANDS

The principle of measurements made for the core can be performed also inside the stable islands, to measure their non-linear parameters. In this case dedicated sextupoles for MTE are turned on. It should be stressed that during normal MTE operation a combination of octupoles and sextupoles are used to generate large stable islands around the closed orbit, but for MTE test measurements the octupolar component created by PS main magnets is sufficient to create sizeable islands. One pencil, single-bunch beam (see Table 1) is kicked inside one island. Fig. 6 (top) shows one example of islands' orbits during 5000 turns. The first part of the plot represents the closed orbit before the kick. Then just after the kick, de-coherence oscillations are clearly visible also with a re-coherence part at the end of the 5000 turns. The same technique that was used for the kicked core has been applied to the islands to extract and fit the centroid oscillations for each island. Fig. 6 (bottom) shows one acquisition for one island and the corresponding chromaticity and detuning fit applied to it. The fit parameters are summarised in Table 3. These values should be compared with -2.78 (chromaticity) and $-708\,\mu\mathrm{m}^{-1}$ (detuning with amplitude) from the model: the agreement is very good.

Beam orbits during de-coherence around islands were also used to determine the detuning with amplitude giving $-887\,\mu\mathrm{m}^{-1}$ in very good agreement with the value from the fit of the centroid motion.

Furthermore, the secondary island tune was also computed, giving 0.019 in good agreement with the model.

Table 3: Comparison Between Fit and Model for Chromaticity and Detuning for Islands; Fit Errors Are Also Quoted

Island	Chromaticity	Detuning ($\mu\mathrm{m}^{-1}$)
1	-2.69 ± 0.15	-988 ± 320
2	-2.78 ± 0.19	-1008 ± 200
3	-2.34 ± 0.11	-840 ± 157
4	-2.34 ± 0.11	-880 ± 157

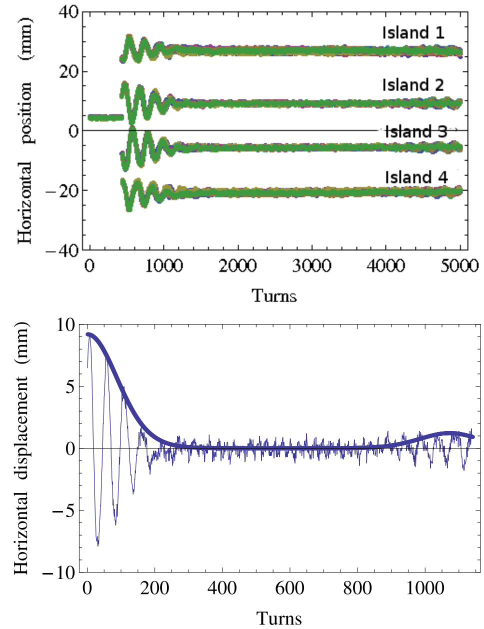

Figure 6: (Top) Trajectories oscillating at the centre of the stable islands during 5000 turns as measured at the pick-up in section 80. (Bottom) Zoom of the initial orbit oscillation for Island 3 together with the fit of the de-coherence. The pick-up used is the one in section 15 to enhance the sensitivity of the analysis.

CONCLUSIONS

Several measurements of non-linear optical properties of the CERN PS lattice have been reported. In general a good agreement is found between the measurement results and the model set-up by trying to reproduce non-linear chromaticity measurements by means of virtual non-linear multipoles next to the PS combined function main magnets.

In the case of detuning with amplitude for the core, a sizeable discrepancy with the model predictions is found. A possible explanation could be that Eq. (1), at the core of most of the analysis, is valid for a lattice in which horizontal/vertical coupling is negligible. For the PS this is certainly the case for linear coupling, but the non-linearities do induce coupling effects. Investigations on this topic will be carried out in the future.

ACKNOWLEDGEMENTS

We would like to thank the PS operation crew and the BI group for support during the measurements.

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ISBN 978-3-95450-115-1