CERN PS OPTICAL PROPERTIES MEASURED WITH TURN-BY-TURN ORBIT DATA

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Abstract

The performance of the CERN Proton Synchrotron (PS) has been constantly increasing over the years both in terms of beam parameters (intensity and brightness) and beam manipulations (transverse and longitudinal splitting). This implies a very good knowledge of the linear and non-linear model of the ring. In this paper we report on a detailed campaign of beam measurements based on turn-by-turn orbit data aimed at measuring the optics in several conditions as well as the resonance driving terms.

INTRODUCTION

In spite of its age, the CERN PS machine is constantly pushed to outperform with respect to the original goals. This is the case for the high-brightness beam required for the LHC and also for the special beam manipulations required for the proposed Multi-Turn Extraction (MTE) [1] that should replace the Continuous Transfer (CT) process to deliver the beams for fixed target physics at the SPS. This novel extraction method is based on transverse beam splitting by means of resonance crossing [2]. Such a method requires a precise knowledge of the PS model, in particular the non-linear one, which explains why systematic measurement campaigns, aimed at reproducing the behaviour of the tune vs. momentum offset, have been launched since 2003 [3] to construct such a model. In parallel, efforts have been devoted to an accurate modelling of the magnetic behaviour of the PS main magnet, including also the special circuits, the so-called pole-face-windings and figure-of-eight loop [4].

Recently [5], the non-linear dynamics has been probed by means of kicking the beam to high amplitude and analysing the decoherence data to extract chromaticity and detuning with amplitude [6]. In this paper those studies have been pursued by performing the first beta-beating measurements for the PS ring and, what is even more relevant, the first measurements of Resonant Driving Terms (RDTs, see, e.g., Refs. [7, 8]), for both sextupolar and octupolar horizontal resonances. It is worth stressing that the latter has never been measured so far in machines in operation [9, 10].

These measurements have been performed using a single bunch proton beam, whose properties are listed in Table 1.

BETA-BEATING MEASUREMENTS

The β-beating is figure-of-merit used to quantify the agreement between the measured and design optics. Its

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

definition is given by $\Delta\beta/\beta = (\beta_{\mathrm{Measurement}} - \beta_{\mathrm{Nom}})/\beta_{\mathrm{Nom}}$. The measurements have been done by kicking the bunch transversally and by acquiring the turn-by-turn orbit evolution over the 40 pick-ups (BPM) of the PS orbit system. The techniques and the software tools used to compute the β-beating are described in Ref. [11].

Figure 1 shows the measured β-beating for the PS ring at 14 GeV/c. Overall, very small values are found, the horizontal and vertical β-beating being compatible with zero, with peak values of only few percent. This confirms the excellent quality of the PS main magnets. The error bars are evaluated based on the beta-measurement obtained by using different groups of BPMs and using also information from several repeated measurements. Even more interest-

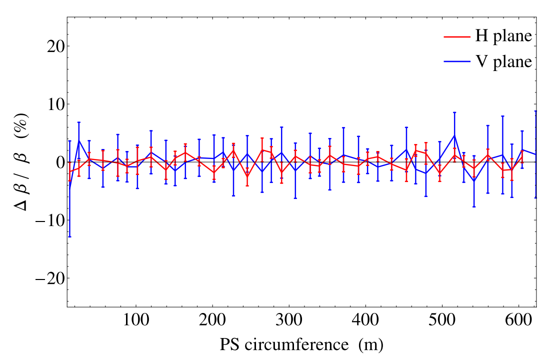

Figure 1: Measured β-beating for the PS ring at 14 GeV/c.

ing is the result obtained for the case when the bunch is displaced into a stable island in the horizontal plane generated by sextupolar and octupolar magnetic fields. By properly setting the horizontal tune, indeed it is possible to generate well-separated islands; the bunch is then displaced into one island by means of a kicker; finally the bunch remains in the islands generating a long-lasting coherent signal as detected by the orbit system. The results of these measurements are shown in Fig. 2. It is worth stressing that under these new conditions the bunch motion in the horizontal plane is periodic over four-machine turns. This explains why the horizontal β-beating is given over four turn and the vertical one provides results over one single turn. Once

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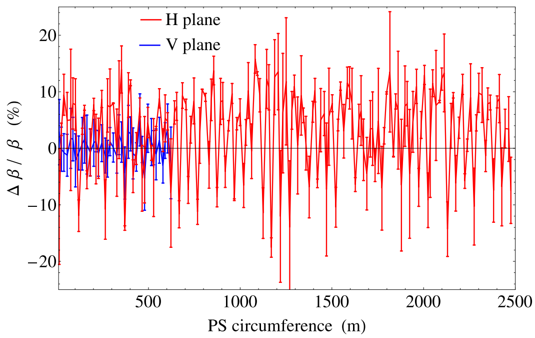

Figure 2: Measured β-beating for a bunch kicked inside a stable island generated at 14 GeV/c (The PS circumference is $2\,\pi 100$ m long).

more, the vertical plane features a close to zero beating, which is a consequence of the very small non-linear coupling between the two transverse planes. In the horizontal plane, however, the β-beating is much larger than for the plain machine configuration and no longer compatible with zero beating. In this case, the reference optics is derived from the motion around the fixed points of the fourth-order resonance as given by computations performed with the MAD-X/PTC code [12]. This observation could mean that the non-linear model might need some revision.

RESONANCE DRIVING TERMS MEASUREMENTS

In addition to the computation of the β-beating, turn-by-turn orbit data have been recorded for various beam excitations in order to probe non-linear dynamics in several conditions. The bunch is excited at different transverse amplitudes and the turn-by-turn data are Fourier-analysed to obtain the amplitudes of the various spectral lines. All measurements have been performed in the horizontal plane as no device to provide a strong enough vertical excitation is available in the PS (the tune kicker and the transverse damper are too weak for this purpose, at least at 14 GeV/c). For all the configuration probed with measurements, numerical simulations have been performed in order to benchmark the experimental results. As for the β-beating, the software package for optics measurements developed for the CERN LHC has been applied to both measurements and tracking data [11].

The first configuration considered includes the special setting of the pole-face-windings and figure-of-eight loop used to generate the islands in the framework of the MTE studies. Therefore, only distributed non-linearities are considered as the two groups of sextupoles and octupoles are not turned on. The extraction kicker has been used with varying excitation amplitude. It is worth noting that a discrepancy appears at high kick amplitude between linear chromaticity given by the model and linear chromaticity computed by beam decoherence analysis using combination of linear chromaticity and first order detuning with amplitude [6]. This observation could be explained by considering that the chromo-geometric term in the tune expression is not accurately reproduced by the non-linear model, as it is based on fitting the measurement of the non-linear chromaticity at zero betatronic amplitude. An additional cross-check of the quality of the non-linear model has been performed via detuning measurement, which was carried out by extracting the tune information 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, providing a detuning with amplitude in agreement with the value given by the model. Figure 3 shows the RDTs as a function of the Courant and Snyder invariant (J) for octupolar ($4\,Q_x = k$) and sextupolar ($3\,Q_x = k$) resonances with results from beam measurements and simulations in both cases. Each value corresponds to weighted average on all PS pickups with error bar corresponding to standard deviation due to different measurements. As expected, the octupolar RDT

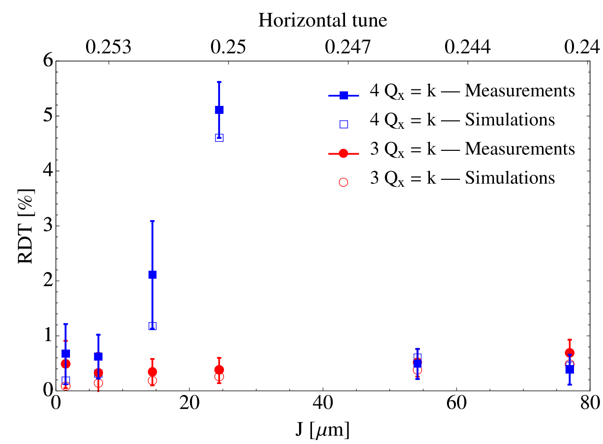

Figure 3: RDT vs. J for sextupolar and octupolar resonances for the standard PS configuration at 14 GeV/c. Both measurements and simulations results are shown for the sake of comparison. The measured tune is reported in the second horizontal scale.

increases with amplitude up to the resonant tune value and then it decreases to zero, while the sextupolar one is always close to zero. This is a natural consequence of the PS configuration with octupolar components excited in the main dipoles to generate the fourth-order stable islands required for beam trapping. The second horizontal scale in Fig. 3 shows the tune value as derived from the data by harmonic analysis. A striking agreement between measurements and simulations is clearly visible.

After this test, the kick amplitude has been fixed at $J = 54.2\ \mu$m and a scan of the linear tune performed by means of the figure-of-eight loop. This coil is supposed to have a strong effect on the two tunes, which are moved to opposite directions, without affecting the non-linear components. Figure 4 shows analysis results for octupolar and sextupolar spectral line during the scan, showing as before the clear presence of an octupolar effect, without any sextupolar one. In this case the agreement between measurements and simulations is not as good as in the previous case. Another test has been done using the extraction kicker with fixed

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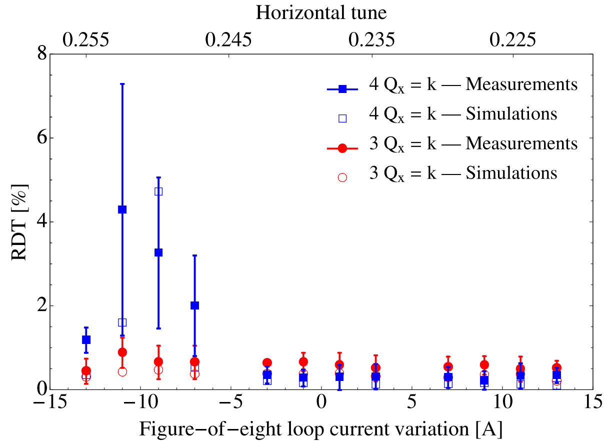

Figure 4: RDT vs. figure-of-eight loop current variation for sextupolar and octupolar resonances for the standard PS configuration at 14 GeV/*c*. Both measurements and simulations results are shown for the sake of comparison. The measured tune is reported in the second horizontal scale.

kick amplitude corresponding to $J = 54.2\ \mu$m and different values of the beam momentum offset, whose results are shown in Fig. 5. A very good agreement between measurements and simulations is found apart from the two cases corresponding to the extreme values of momentum offset.

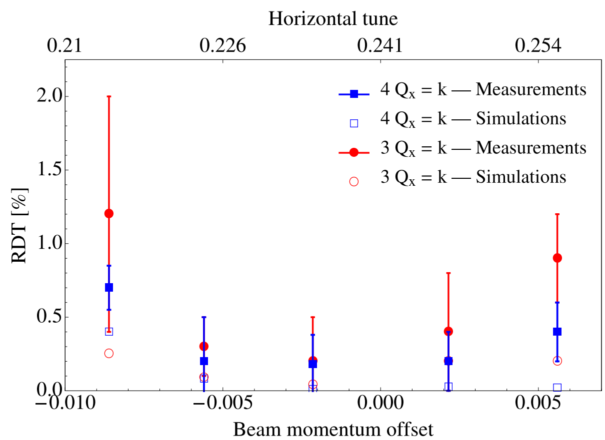

Figure 5: RDT vs. beam momentum offset for sextupolar and octupolar resonances for the standard PS configuration at 14 GeV/*c*. Both measurements and simulations results are shown for the sake of comparison. The measured tune is reported in the second horizontal scale.

A different type of tests has been performed by turning on two sextupoles used to generate stable islands for MTE. Once more, a scan over the transverse amplitude has been performed and the results are shown in Fig. 6. It is also apparent that the agreement is everywhere very good apart from the point at low amplitude, which is the configuration most affected by noise and other effects.

CONCLUSIONS

The first measurements of β-beating in the PS have been performed, both for standard beams and for the optics of the islands corresponding to a stable fourth-order resonance. In addition, RDT measurements for various PS machine configurations have been performed, which represent a first-time result. Such an achievement is particularly successful thanks to the special conditions required for the MTE gymnastics, which have allowed octupolar RDTs to be clearly identified from the experimental data.

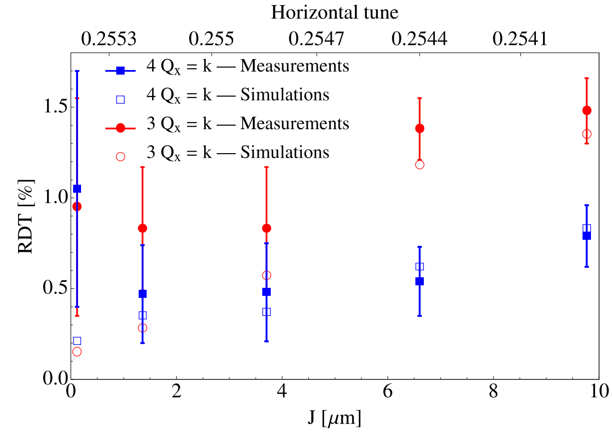

Figure 6: RDT vs. J for sextupolar and octupolar resonances in the case of the standard PS configuration at 14 GeV/*c* with additional single sextupole magnets turned on. Both measurements and simulations results are shown for the sake of comparison. The measured tune is reported in the second horizontal scale.

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