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LINEAR AND NON-LINEAR OPTICS MEASUREMENTS IN PS USING TURN-BY-TURN BPM DATA

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Abstract

For the first time, the optics of the CERN Proton Synchrotron (PS) was measured using turn-by-turn BPM data of forced betatron oscillations excited with an AC dipole. We report results of phase advance and beta-beating measurements. Linear coupling was globally minimised along the machine by measuring and correcting coupling resonance driving terms. Finally, non-linear properties of the ring were probed looking at third- and fourth-order resonance driving terms and amplitude detuning.

INTRODUCTION

Even though the CERN Proton Synchrotron serves beams since 1959 [1] several beam dynamics aspects need further investigations. In this paper we report on a detailed optics-measurement campaign that was carried out in 2018, with the goal of understanding machine reproducibility, dynamic effects during the collapse of the injection bump and at the start of acceleration, as well as non-linear effects in the beam dynamics. A first study was carried out in 2012 [2] and focused only on the determination of the typical beta beating and resonant driving terms using a transverse kicker to excite the beam.

The algorithms and tools implemented for the LHC beam commissioning [3–9] showed their power in action [10–13]. Recently, these tools have been adapted for use for the CERN Proton Synchrotron (PS) and Proton Synchrotron Booster (PSB) such that turn-by-turn BPM data can be analysed in an automatised manner [3–9].

Betatron oscillations need to be excited in both transverse planes. The most common mean of bunch excitation is a kicker magnet, however, only horizontal kickers are available in the PS ring as the vertical one was decommissioned several years ago. Another option is use of injection oscillations that work for both planes, but this limits the studies to a short lapse of time at the very beginning of a cycle. Alternatively, an AC dipole (ACD) can be used, which excites the beam continuously with a frequency close to the tune. The PS transverse feedback (TFB) system was equipped with two dedicated waveform generators to implement ACD so that studies could be carried out at any time along a cycle.

Only 50% to 70% of the maximum TFB strength could be used for the measurements due to a too strong distortion of the waveform at larger amplitudes. The distance of the ACD frequency from the betatron tune has impact on the oscillations' amplitude and, in case of tune drifts, the oscillation is not constant, eventually leading to beam losses and reduced measurement accuracy. At injection (1.4 GeV kinetic energy) the best accuracy was found for a distance of 4×10^{-3} in tune units, which provides betatron oscillations of approximately 1 mm. This is fully sufficient for linear optics measurements, but not enough to measure sextupolar or octupolar Resonant Driving Terms (RDTs). For higher energies, the kick strength proportionally decreases, however, the PS tune stability improves such that the distance between ACD and tune frequencies can be smaller (1×10^{-3}) and again, oscillations with 1 mm amplitude can be achieved.

Each measurement was repeated for 10 to 20 times to provide a reliable estimate of the reproducibility. Amplitude and phase of each spectral line is obtained as an average of individual values and uncertainties are defined as the r.m.s. value. These errors are then propagated when calculating the optical functions, including also systematic errors due, e.g. to the uncertainty of the transfer matrix in between the BPMs. The details of the algorithms and of the computational procedures are described in [3–9].

Various PS ring configurations with different beam conditions were measured during the campaign. In most of the cases presented in this paper, a single bunch with intensity in range $15 - 25 \times 10^{10}$ protons per bunch (ppb) was used. The harmonic number was 8 or 9, except for Multi Turn Extraction (MTE) cycle which had all 16 buckets filled and the intensity was 7×10^{10} ppb.

For turn-by-turn analysis, it is most convenient to define the beginning of the PS lattice at the first BPM after injection. Therefore in all plots the starting point of the PS ring is the BPM in straight section 43.

LINEAR OPTICS

Various types of beams, produced with different PS configurations, were measured and for most of the cases the resolution of phase advance between BPM pairs was below $5 \times 10^{-4}\ 2\pi$ or $3 \times 10^{-4}\ 2\pi$ for the horizontal or vertical plane, respectively. Beta functions were reconstructed with a relative accuracy below 0.25% and 0.15%, respectively.

A small beta beating was confirmed [2] with the maximum peak value reaching 7%, while for most of the PS configurations it is below 3%. Comparison with K-modulation was also performed and a good agreement between the two techniques was found. The measurements determined the optical parameters at the location of the wire scanners to improve the accuracy of the emittance determination and they provided a verification of the calibration of the correction quadrupoles.

Motivated by the qualitative observation of a tune change as a function of the preceding cycle, the optics was measured to understand quantitatively this effect. A dedicated cycle with low chromaticity was setup to observe injection oscillations of 10 mm amplitude in both planes. This allowed to probe 3rd and 4th order RDTs. Four cycles, immediately

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preceding that for which measurements were carried out, were probed: the so-called Zero, which is a placeholder not accelerating any beam and ramping the main magnets only to 10% of the injection value; MTE, which is accelerating the beam to 14 GeV/c and splits it transversely [14, 15]; TOF, which accelerates the beam to 20 GeV/c for delivery to the lead target of the Time-Of-Flight facility at CERN; LHC, which accelerates the beam to 26 GeV/c for injection in the SPS and then LHC. While the BPM-to-BPM phase beating, and therefore also beta beating, was found to be independent on the preceding cycle within the error bars, the total phase advance in the horizontal plane, i.e. the tune, features a clear difference as it is seen in Fig. 1. The effect in the vertical plane was much less pronounced.

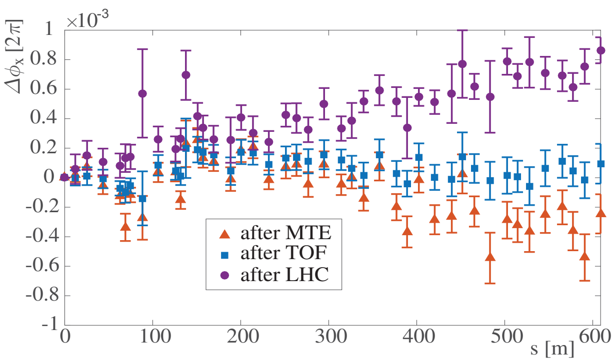

Figure 1: Horizontal variation of phase advance ($\Delta\phi_x$) for different preceding cycles with respect to Zero cycle.

LINEAR COUPLING

The linear coupling RDTs f_{1001} and f_{1010} are reconstructed at each BPM using the algorithm described in [16, 17]. This method is superior with respect to a measurement performed using a tune monitor as it allows to localise coupling sources so to find a correction that minimises the RDTs all along the machine circumference [18].

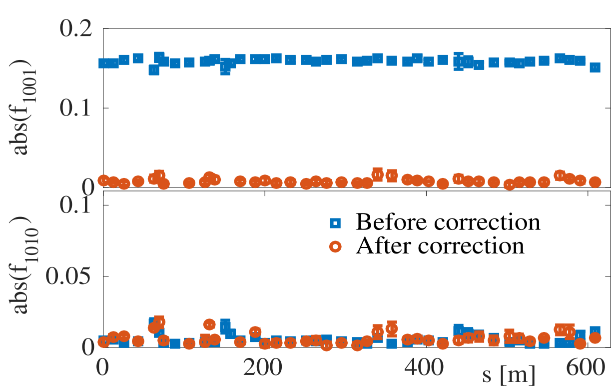

Figure 2: Coupling RDTs before and after correction.

An example measurement, together with the result of correction, is presented in Fig. 2, where the mean uncertainty of RDT amplitude is around 3×10^{-3}. It is clear that coupling errors are uniformly distributed along the PS ring, as the RDT values are not changing abruptly at any location. The first correction was able to reduce the amplitude of f_{1001} to below 1×10^{-2} and the second iteration could not improve it any further.

Figure 3 compares the strength of the skew quadrupoles used to minimise the RDTs with those used to correct coupling for the operational beams. The latter one was obtained with the closest tune approach method, for which the skew quadrupoles were grouped in two families. The results are very similar, even though the nominal setting has strengths that are about 10% stronger.

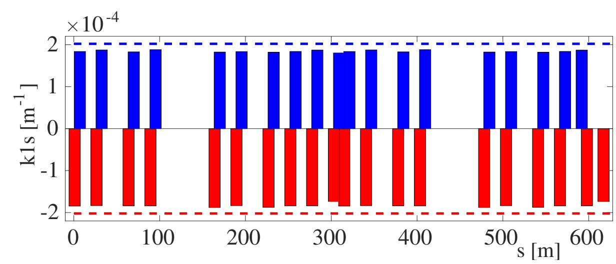

Figure 3: Strength of the skew quadrupoles required by the correction shown in Fig. 2. The two colours indicate the composition of the two families of correctors. Dashed lines mark values used to correct linear coupling for the operational beams, which is the same for all the magnets.

RESONANCE DRIVING TERMS

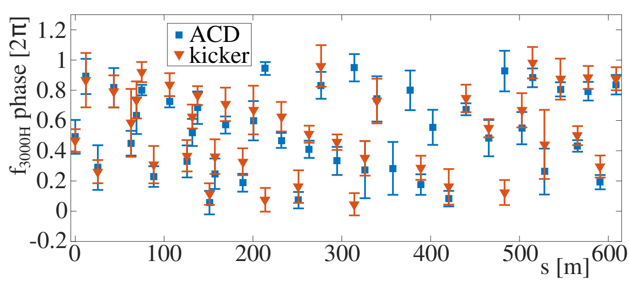

Figure 4: RDT f_{3000} phase measured with ACD and kicker for the MTE cycle at 14 GeV/c.

One of the main motivations for these studies is a better understanding of the PS non-linearities. However, the ACD turns out to be too weak to reach a satisfactory accuracy of RDT measurement. For the MTE cycle, which employs sextupoles and octupoles to create islands in the horizontal phase space at 14 GeV/c, only four sextupole RDTs could be measured with phase resolution below $3\times10^{-1}2\pi$. These are connected with two spectral lines, namely horizontal $2Q_x$ (f_{3000} and f_{1200}) and vertical $Q_x - Q_y$ (f_{1011} and f_{0120}). Figure 4 compares f_{3000} phase measured with ACD and a kicker and gives an idea about quality of the measurements. In comparison, the $3Q_x$ line is well visible and f_{4000} and f_{1300} are measured with satisfactory accuracy when the beam is excited by means of the kicker, but it is not detected with ACD data. Moreover, the ACD is also too weak to measure amplitude detuning.

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On the other hand, the RDTs could be well measured with injection oscillations. A special configuration of the PS ring derived from the TOF cycle was used, in which the chromaticity was lowered using the Pole-Face-Windings (PFW) and a single lattice sextupole to reduce decoherence. This way, for the beam injected with 10 mm offset, oscillations were still above 4 mm after 5000 turns.

Normal and skew sextupole magnets were powered in several configurations to find the measurement sensitivity by trying to detect the sources of the RDTs. Machine tunes were set below 0.33 to enhance the non-linear motion. In these conditions amplitude and phase resolution reached 1% and $1 \times 10^{-2} 2\pi$, respectively. Figure 6 shows an example measurement. The model reproduces well the phases of sextupolar RDTs when lattice sextupoles are powered.

Six out of eight skew sextupole RDTs (f_{1110H}, f_{1101H}, f_{2001H}, f_{0210H}, f_{2010H} and f_{2010V}) were measured with a good resolution even when all skew sextupole were switched off. In the best cases the mean phase error was below $4 \times 10^{-2} 2\pi$ and in general it was below $1 \times 10^{-1} 2\pi$. The RDT f_{2010}, which is measured independently using the horizontal and vertical spectra, was the same within the error bars, what gives confidence in this result. Indeed, magnetic measurements of the main magnets indicated a skew sextupole component at the edges. Its strength is comparable with the sensitivity of the used magnetic probe, therefore the uncertainty is rather large. Thin skew sextupoles were added in the model at the edges of the main magnets. Their integrated strength was matched to reproduce the measured RDTs. We found that values $-2 \times 10^{-5}\, m^{-2}$ for the focusing magnet units and $+1 \times 10^{-5}\, m^{-2}$ for the defocusing ones reproduce well the measurement. Because chromaticity was not fully corrected, which modifies by some factor the measured RDT amplitudes [4], the model and the measurements cannot be exactly compared. By observing RDT amplitude discrepancy between the model and the measurement when lattice sextupoles are powered we expect a factor 2 to 3. Therefore, additional measurements are required to precisely determine the strength of the skew sextupole component in the main magnets.

DYNAMIC EFFECTS DURING INJECTION BUMP

During injection a tune variation of almost 10^{-2} is observed [19], which might be generated by feed-down effects of the sextupolar eddy currents in the vacuum chambers of the bumper magnets. To understand better the phenomenon, injection oscillations were examined over short ranges of turns corresponding to injection (turns 2-200), bump collapse (200-450), and regular orbit (2000-4000). Three working points were measured to better understand the evolution of RDTs. The measured phase and beta beating indeed are changing, see Fig. 5 for tunes 0.32/0.29. Sextupolar and octupolar RDTs are also clearly modified, both in amplitude and phase. Figure 6 shows RDT f_{1020V} as an example.

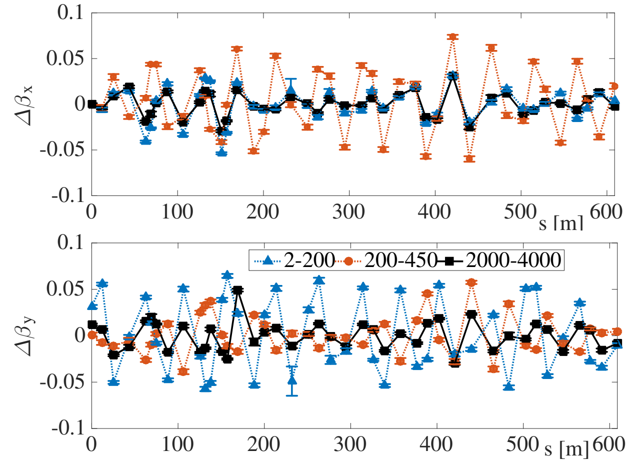

Figure 5: Beta-beating ($\Delta\beta = \frac{\beta_{me}-\beta_{mo}}{\beta_{mo}}$) for different ranges of turns after injection. β_{me} and β_{mo} are measured and model values, respectively.

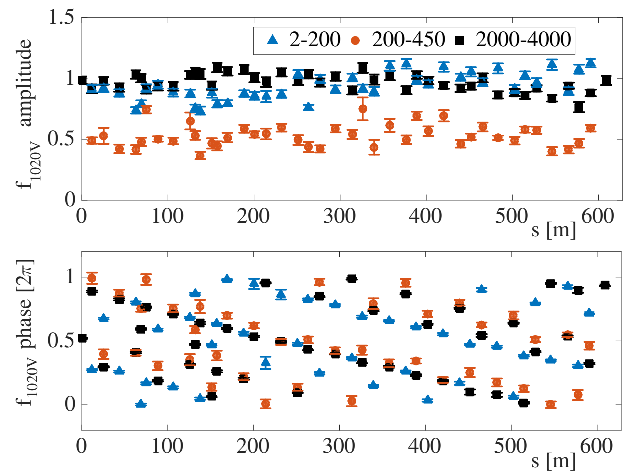

Figure 6: RDT f_{1020V} amplitude (top) and phase (bottom) for different ranges of turns after injection.

However, the study is not yet conclusive concerning the reconstruction of the errors and their locations.

CONCLUSIONS

The CERN software tools for optics measurements and corrections in the LHC were successfully adapted to the PS, streamlining the overall analysis process.

A measurement campaign based on turn-by-turn bunch position analysis was carried out to measure the detail of the PS beam dynamics. For the first time ACD excitation was employed allowing for accurate linear optics measurements and local corrections of the linear coupling.

The ACD strength turned out to be insufficient to measure RDTs as accurately as it was hoped for, and only a subset of spectral lines could be observed. On the other hand, RDTs were measured with a good accuracy by means of betatron oscillations induced by a kicker or a mis-steered injection. The detailed study of these measurements is still in progress and will provide insight on non-linear dynamics in PS.

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