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OPTICS MEASUREMENT BY EXCITATION OF BETATRON OSCILLATIONS IN THE CERN PSB

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Abstract

Optics measurement from analysis of turn-by-turn BPM data of betatron oscillations excited with a kicker magnet has been employed very successfully in many machines, but faces particular challenges in the CERN PSB where BPM to BPM phase advances are sub-optimal for optics reconstruction. Experience using turn-by-turn oscillation data for linear optics measurements during PSB commissioning in 2021 is presented, with implications for the prospect of such techniques in the PSB more generally.

INTRODUCTION

The CERN Proton Synchrotron Booster (PSB) typically operates at integer $Q_{x,y} = 4$, with 16 dual-plane BPMs spaced by $\Delta\phi \approx 90°$ [1, 2]. K-modulation of individually powered quads has been used during commissioning in 2021 to study vertical β-beat in the injection region [3–6], however optics measurement via turn-by-turn (TbT) BPM data [7] has proved extremely successful in other machines (notably at CERN for the LHC [8–11]) and is also of interest to the PSB. The favoured method is reconstruction of β-beat from measurement of inter-BPM phase advances (the N-BPM method [12, 13]), however uncertainty on the reconstructed β diverges as $\Delta\phi$ approaches 90° [12]. Figure 1 shows an example of reconstructed β-beat from ideal tracking data in PSB simulations with $\Delta\beta/\beta \approx 0.05$. With existing BPMs (red) systematic errors on the reconstruction reach $\sigma(\Delta\beta/\beta) \approx 0.4$. This could be improved by addition of more BPMs, and Fig. 1 (blue) shows the improvement which could be expected upon addition of 5 BPMs at optimal $\Delta\phi$. With existing PSB hardware however, the N-BPM method is inviable at the nominal working point (WP).

Alternatively, β-beat can be reconstructed from the amplitude of excited betatron oscillations (β-from-amp) [7]. This method is not limited by inter-BPM $\Delta\phi$, but is susceptible to BPM calibration errors and benefits from beam-based checks of BPM calibration [14] which could not yet be performed. Inter-BPM phase advance can also be studied directly, typically with respect to a reference measurement or model (phase-beating). During 2021 PSB commissioning TbT optics measurement (with particular emphasis on phase-beating) were performed using injection oscillations and active excitation by Q-kicker and AC-dipole [15, 16].

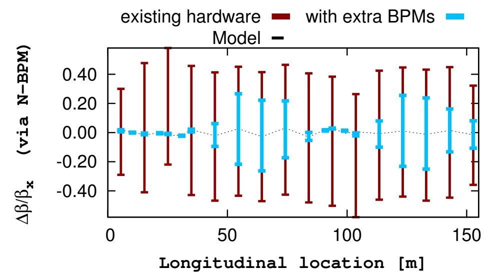

Figure 1: β-beat via N-BPM method for ideal tracking simulations with existing PSB BPMs (red), and with extra BPMs (blue) at optimal $\Delta\phi$ in periods 1, 2, 3, 10 and 11. Error bars are the systematic uncertainty on the reconstruction.

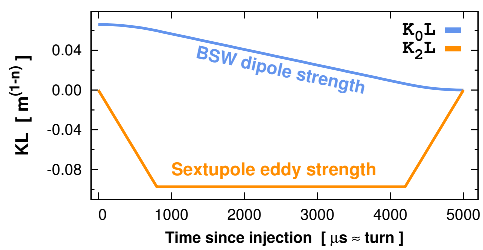

Figure 2: Integrated dipole and sextupole strength during collapse of injection (BSW) orbit bump.

STUDY OF INJECTION BUMP COLLAPSE VIA INJECTION OSCILLATIONS

In the PSB H^- injection scheme [2] the injection (BSW) orbit bump collapses over 5000 turns, generating sextupole eddy currents proportional to the ramp rate [17]. This sextupole component changes rapidly during the first several hundred turns of the BSW collapse (Fig. 2) potentially generating an optics change via feed-down. This has been studied via analysis of injection oscillations. Figure 3 (left, red) shows measured TbT data following injection of the beam. Available turns for analysis are limited by electrical noise and orbit leakage at Turn = 150 caused by collapse of a separate painting bump [2]. Nonetheless Fig. 3 (right) shows a high-quality measurement of phase-beat is obtained, with good reproducibility from injection to injection (the maximum range of phase-beat over 20 injections is indicated by the shaded area).

By changing the start time of the BSW collapse (so injection occurs as collapse is under way) optics changes from the BSW can be examined. Changing BSW timing alters injection oscillation amplitude (Fig. 3, left, red-vs-blue). Figure 4

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(top) shows peak-to-peak oscillation amplitude changing vs the BSW timing, with the decay beginning at ≈ −200 s (where 1 s ≈ 1 turn). Figure 4 (bottom) shows the difference of horizontal inter-BPM phase advance measured for different BSW timings, with respect to a reference setting ($t = 0$ s). During the BSW plateau the optics is very stable, but a rapid change to phase-beat is observed with the start of the BSW decay. Interestingly the observed optics change with BSW decay is significantly larger than expected from the nominal model (cyan area in Fig. 4 indicates the maximum expected phase-change during BSW decay). Complementary measurements of Q_x shifts during BSW collapse were performed (Fig. 5), which also showed larger variation than expected from modelled feed-down (red). These observations are suggestive of an issue with modelled feed-down from sextupole eddy currents during injection bump collapse, and while not significant for operation represent an interesting avenue for further study of the optics model.

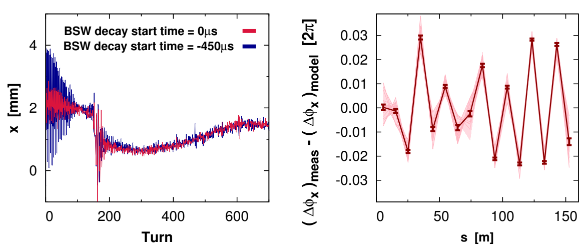

Figure 3: Left: example of injection oscillations for nominal timing of the BSW decay (red) and with the start time of the BSW decay shifted forwards by 450 s (blue). Right: phase-beating with respect to nominal PSB model measured from injection oscillations, shaded area indicates the range of phase-beat measured over 20 injections at $Q_x = 4.40$.

MEASUREMENTS WITH TUNE KICKER AT FLAT-BOTTOM

TbT optics measurement at flat-bottom (after collapse of the injection bumps) requires active excitation. In PSB a Q-kicker can provide this, and Fig. 6 shows an example of TbT data for the maximum possible excitation at 160 MeV. Attempts to measure vertical phase-beating in the nominal configuration were unsuccessful due to a combination of rapid decoherence and poor sampling of the oscillation at the nominal WP of $Q_y = 4.45$. Future optics study in the V-plane will require optimization of the measurement configuration. In the H-plane (at WP $Q_x = 4.40$) however, good measurements of phase-beat could be obtained at flat-bottom. Figure 7 shows average and standard error of horizontal phase-beating (w.r.t. the model) measured over multiple injections via the Q-kicker. Measurements were performed on a flat PSB cycle (without energy ramp) at Turn = 7000 just after collapse of all injection bumps (pale colors) and later at Turn = 15000 (dark colors). Two sets of measurement were performed on the same cycle separated by 3 weeks (purple and red). Good consistency is observed between the measurements both during the flat-bottom period and over time, which bodes well for study of error sources.

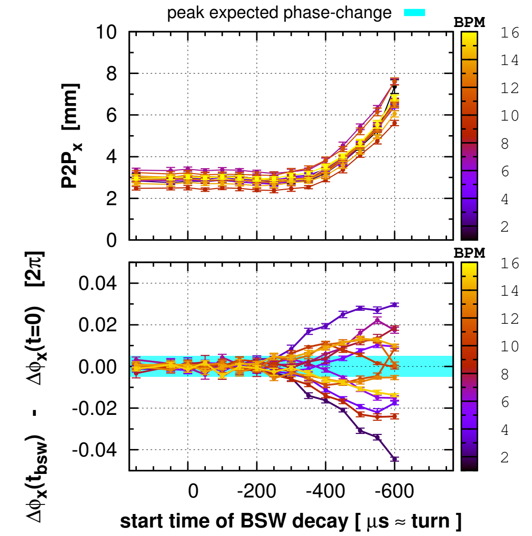

Figure 4: Change to horizontal inter-BPM phase advance ($\Delta\phi_x$) measured for different start time of BSW decay, with respect to value at nominal timing ($\Delta\phi_x(t = 0)$).

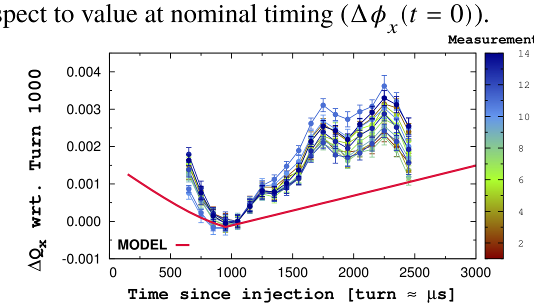

Figure 5: ΔQ_x (w.r.t. Q_x after 1000 turns) vs time since injection. Data points are measurement for each injection. Errors are RMS over 16 BPMs for each measurement.

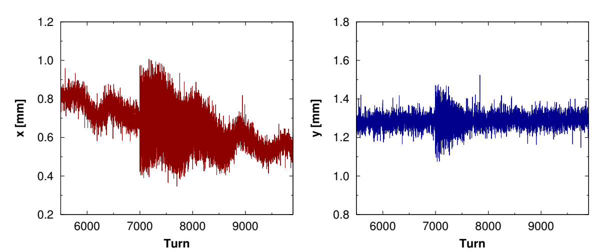

Figure 6: Example of TbT data at 160 MeV with $Q_{x,y}$ = 4.40, 4.45 and maximum powering of the Q-kicker.

The phase-beat measured in Fig. 7 at the working point (4.40, 4.45) is larger than measured in Run 2 during dedicated optics tests at 160 MeV [18, 19], which showed $(\Delta\phi_{meas} - \Delta\phi_{model}) \leq 0.01$. Tests in Run 2 however, were performed at WP further from the half integer resonance ($Q_x \approx 4.2$). Figure 8 shows phase-beat (w.r.t. model) at Q_x = 4.4, 4.3, and 4.2 (model tunes are changed to reflect the applied WP). Moving away from the half-integer, a reduction in phase-beat is observed, and at $Q_x = 4.2$ the amplitude of the horizontal phase-beating is comparable to that observed in dedicated tests in 2018.

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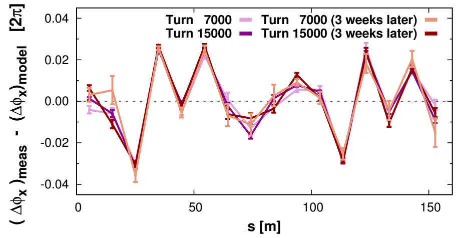

Figure 7: Reproducibility of horizontal phase-beat at flat-bottom turn 7000 and turn 15000 over 3 week period.

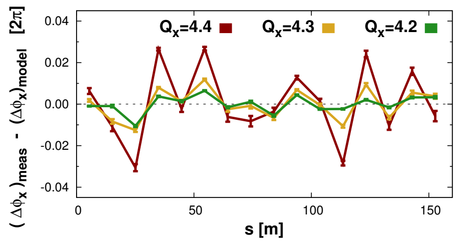

Figure 8: Dependence of horizontal phase-beat on working point at flat-bottom turn 15000.

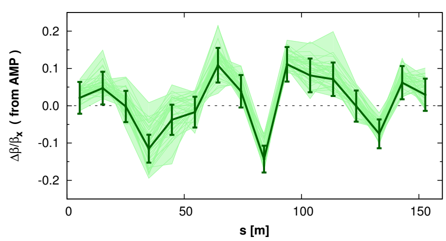

Figure 9: Measured β-beat from amplitude under optimal conditions with the Q-kicker. Error-bars are combination of std. over 30 injections together with uncertainty on reconstruction from error on action measurement. Shaded area indicates range of β-beat measured over 30 injections.

As beam-based BPM calibration was not yet possible, PSB commissioning with TbT data focused on phase-beating. Figure 9 shows however, that a reasonable precision of the β-beat (from-AMP) could be achieved under good conditions (with ~ 0.5 mm kick amplitude at the BPMs, $Q_x = 4.208$). Precision on the β-beat of $\sigma(\Delta\beta/\beta) \leq 0.05$ was achievable, which should allow study of optics via β-from-amp once beam-based calibration is available [14].

EXPERIENCE WITH AC-DIPOLE KICKS

AC-dipole kicks (provided by transverse feed-back) can provide high-quality optics measurement by exciting driven motion of the beam at frequencies (Q_{AC}) close to the natural tune (Q_{nat}) for a large number of turns. To limit errors on reconstructed $\Delta\beta/\beta$ to ≤ 1 % however, offsets between Q_{nat} and Q_{AC} should be known to $\Delta Q_{AC-nat} \leq 0.001$. Measurement of Q_{nat} (with the Q-kicker) showed large shot-to-shot variation as seen in Fig. 10. It will be advantageous when measuring optics with an AC-dipole kick therefore, to also measure Q_{nat} (for example with BBQ chirp or Q-kicker immediately before/after AC-dipole kicks). Such procedures are not currently implemented in the PSB, but based on 2021 commissioning experience are being explored.

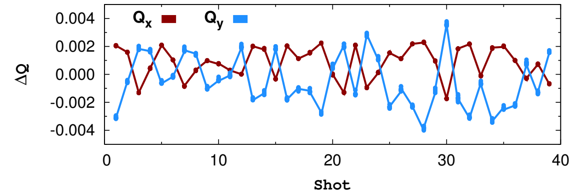

Figure 10: Example of cycle-to-cycle variation of $Q_{x,y}$.

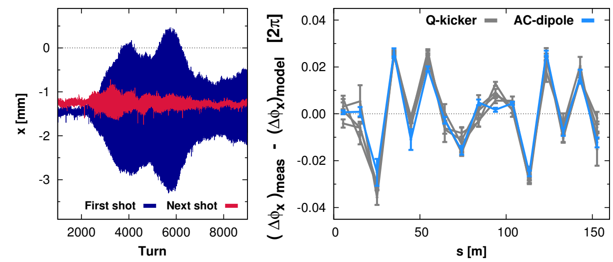

Figure 11: Left: TbT data for 2 consecutive shots with same AC-dipole excitation. Right: comparison of phase-beat at flat-bottom measured with Q-kicker and AC-dipole.

AC-dipole kick amplitude is sensitive to the offset between Q_{nat} and Q_{AC}. Shot-to-shot variations of Q_{nat} therefore cause large variation in kick amplitude. This is seen in Fig. 11 (left) which shows TbT data from 2 different injections under influence of the same AC-dipole excitation between turn 2000 and turn 7000. By careful filtering of the AC-dipole measurements to exclude bad kicks however, a good measurement of phase-beating can still be obtained, and Fig. 11 (right) shows that horizontal phase-beat measured with AC-dipole (blue) is very consistent with that previously measured with the Q-kicker (gray).

CONCLUSIONS

PSB commissioning in 2021 allowed valuable experience of optics measurement from TbT BPM data to be gained. Limitations were identified, notably poor measurement of vertical optics due to rapid decoherence and poor sampling close to the half-integer resonance, and large variability in AC-dipole measurement quality due to non-negligible shot-to-shot variation of natural tune. Nonetheless experience did demonstrate the usefulness of TbT methods (particularly for measurement of phase-beat) with study of injection oscillations suggesting there may exist larger than expected feed-down of sextupole eddy currents during injection bump collapse, and measurements at flat-bottom showing good reproducibility of the phase-beat, which was also compatible with studies from Run 2. Initial studies of β from amplitude were promising but require dedicated studies of beam-based BPM calibration to progress.

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