MEASUREMENT OF TUNE SHIFT WITH AMPLITUDE FROM BPM DATA WITH A SINGLE KICKER PULSE*

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Abstract

Measurements of amplitude-dependent tune shift are critical for understanding of nonlinear single particle dynamics in storage rings. The conventional method involves scanning of the kicker amplitude while having a short bunch train at the top of the kicker pulse. In this paper we present a novel, alternative technique that uses a long continuous bunch train, or a sequence of bunch trains, that are spread along the ring, such that different bunches experience different kick amplitudes with a single shot of a kicker pulse. With these beams, a curve of tune shift with amplitude can be extracted from the recently added new NSLS-II BPM feature called gated turn-by-turn (TbT) BPM data that can resolve bunches within a turn, either alone or together with a bunch-by-bunch BPM data. This technique is immune to pulse-to-pulse jitters and long-term machine drift.

INTRODUCTION

Third-generation light sources utilize strong focusing to achieve an electron beam emittance as small as possible. Stronger focusing leads to more negative natural chromaticity, which needs to be compensated by stronger chromatic sextupoles to have positive chromaticity. Nonlinearity in electron beam motion introduced by strong chromatic sextupoles needs to be then controlled by strong geometric sextupoles or other higher-order multipoles. Otherwise, dynamic aperture and momentum acceptance of the lattice may collapse, resulting in poor injection efficiency and reduced Touschek lifetime. Hence it is important to be able to characterize the nonlinearity of a storage ring lattice. One such nonlinear characterization metric is tune shift with amplitude (TSwA) [1].

Experimental measurement of TSwA can be performed with a single shot of a kicker pulse while obtaining turn-by-turn (TbT) data from which amplitude and tune can be extracted, if coherent damping is faster than decoherence, for example at LEP [1]. This excludes the possibility of measuring tune shift at very large amplitude, since large amplitude inevitably leads to fast decoherence. In order to measure tune shift for large amplitude, multiple shots of TbT data with different kick amplitudes are conventionally required.

CONVENTIONAL APPROACH

A conventional method to measure a TSwA curve for an electron storage ring is to place a short train of electron bunches in a ring and to kick the beam with a fast pinger (kicker) pulse while acquiring a TbT data. Repeating this while gradually increasing the kicker strength until the beam is lost results in a TSwA curve. This multiple-shot measurement setup is depicted in Fig. 1(a). This method is prone to short-term shot-to-shot jitter as well as long-term machine drift due most likely to the limited stability of the power supplies and RF system. This sometimes makes the interpretation of the resulting TSwA curve difficult even for a state-of-the-art facility like NSLS-II, which is found to have tune jitter on the order of 10^{-4} that may not be sufficient for high-precision nonlinear lattice calibration. If we can obtain a TSwA curve with a single shot, these issues can be eliminated completely.

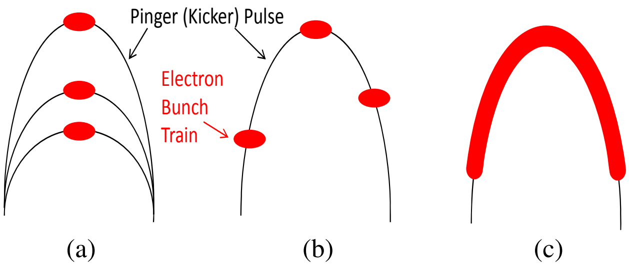

Figure 1: Various setups for measurements of tune shift with amplitude. (a) Conventional multiple-shot setup that is prone to machine jitter and drift. New single-shot setups with trains of bunches (b) discretely placed and (c) continuously placed in a storage ring.

NOVEL SINGLE-SHOT TECHNIQUE

Our single-shot method involves placing trains of bunches either discretely or continuously spread out in the ring as shown in Figs. 1(b) and (c). Due to NSLS-II pingers having half-sine pulses (FWHM of ~0.6 revolution period), these bunches experience different kick strengths. Then we save BPM ADC data from 180 regular RF BPMs

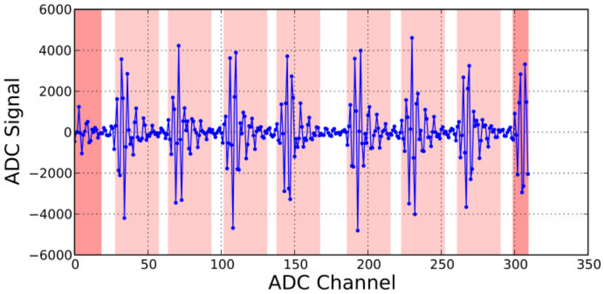

Figure 2: One turn ADC signal from a button of a BPM when 8 trains of bunches are roughly equally spread out in the ring. Shaded regions contain signals of bunch motion. Gating one of these sections and applying the standard TbT extraction process results in TbT position data only for the selected train of bunches.

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synchronized with a pinger pulse. From the ADC data, we can extract "gated TbT" data that can resolve bunches within a turn, a unique new capability of NSLS-II RF BPM that has been recently implemented [2-5]. Figure 2 shows a one-turn ADC signal obtained when 8 trains of 20 bunches were spread out roughly equally throughout the ring. By gating out (i.e., applying a boxcar window on) a section of ADC channels only where a bunch signal exists, and applying the standard TbT position extraction process, TbT position data only for the selected bunches can be extracted. From these gated TbT data, both amplitude and tune can be extracted. Note that given the BPM front-end filter bandwidth limitation, only ~8 trains of bunches can be resolved without having overlapped ADC signals by using this technique for NSLS-II.

EXPERIMENT: CONTINUOUS TRAIN

A continuous train of 1000 bunches (~2 mA) was injected into the ring, leaving 320 RF buckets empty as an ion gap. The fill patterns before and after firing the vertical pinger are shown in Fig. 3. The bunches in the middle were lost because they experienced kicks larger than the dynamic aperture (DA). This demonstrates the capability of a high-resolution single-shot 1-D DA measurement with this setup. Figure 4 shows the extracted gated TbT data for the bunches in the colored rectangles shown in Fig. 3, clearly showing different oscillation amplitudes.

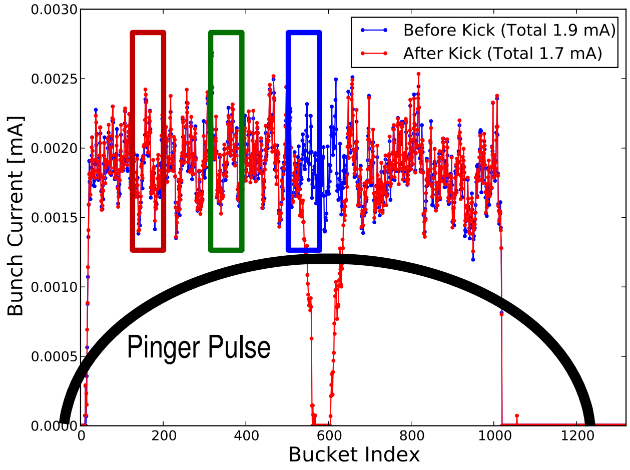

Figure 3: Fill patterns of a continuous train of 1000 bunches before and after a vertical pinger kick, showing loss of bunches that have experienced kicks beyond DA.

The TSwA curve derived from the single-shot gated TbT data is shown as the smooth and continuous curve (blue) in Fig. 5, together with the TSwA curve from the conventional multi-shot method (black). (Note that this black curve is fairly smooth due to having minimum machine drift/jitter during this particular measurement, but this is not the case in general.) The new and conventional curves agree well, but the single-shot curve shows much larger error bars both in amplitude and tune (10^{-4} vs. 10^{-6}). This is because signal leakage from adjacent bunches that are kicked with different amplitudes is corrupting position estimates. This is evident from the fact that the gated TbT data decohere faster if the gating window is widened.

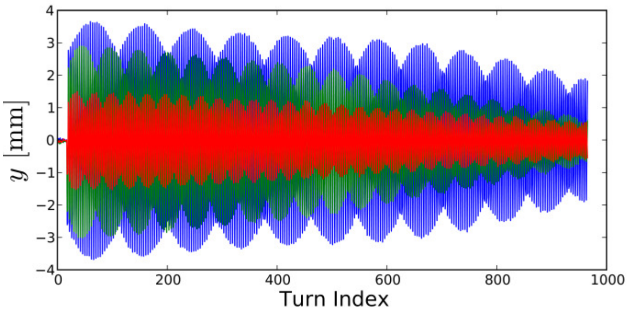

Figure 4: Gated TbT position data for the bunches selected by colored rectangles shown in Fig. 3.

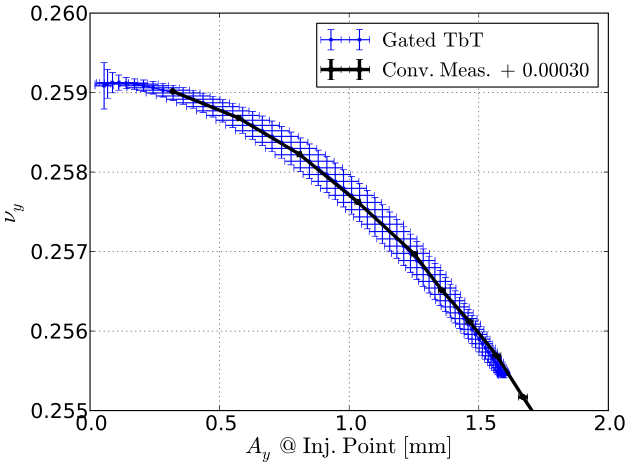

Figure 5: Vertical TSwA curves from the new single-shot method using gated TbT data for 1000-bunch train (blue) and the conventional multi-shot method (black).

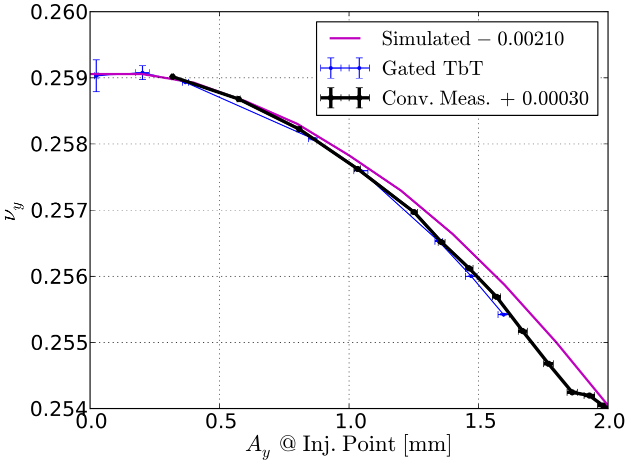

Figure 6: Vertical TSwA curves from the new single-shot method using gated TbT data for 8 trains (blue), the conventional multi-shot method (black), and tracking simulation using Tracy (magenta).

EXPERIMENT: DISCRETE TRAINS

One way to reduce the error bars for the gated-TbT-derived curve is to use discrete trains of bunches spread out throughout the ring so that the signals from neighbour bunches do not corrupt TbT data. The resulting curve when using 8 trains (20 bunches in each train) roughly equally spaced out in the ring is shown in Fig. 6. The error bars in this case are significantly reduced to the same level as those of the conventional method. Furthermore, both the single-shot and conventional vertical TSwA curves are close to the TSwA curve expected from the design model using Tracy [6].

EXPERIMENT: ADDING BxB DIGITIZER

An alternative approach is to use the bunch-by-bunch (BxB) feedback system digitizer, which provides accurate TbT BxB positions for the (single) dedicated BPM used by the system [7]. Data acquisition can be easily synchronized with the pinger kick. While the BxB feedback is necessary during regular operations to suppress transverse coupled bunch instabilities, this feedback was turned off during the low-current measurements described here, and its digitzer was used only as a diagnostic tool.

Figure 7 shows the curves of tune vs. bunch index extracted from BxB data for the case of a 1000-bunch continuous train. The curves are consistent with expectation. On the other hand, oscillation amplitudes extracted from the same data are harder to interpret, possibly due to a very nonlinear BxB system BPM response for a large-amplitude beam offset. To overcome this, we combined the tune data from the BxB data with the amplitude data from the gated TbT data. The resulting combined TSwA curve is shown in Fig. 8, along with the TSwA curve from the gated TbT data alone. These curves agree well. Note that there is a distortion around $\nu_x = 0.2$, which indicates $5\nu_x$ resonance. This resonance line was predicted by a simulated frequency map as shown in Fig. 9. Given the large number of amplitude sampling points, this technique allows detection of a very thin resonance stopband that would be easily missed by the conventional method.

CONCLUSION

Single-shot measurements of tune shift with amplitude (TSwA) have been demonstrated experimentally using gated TbT (recently added capability of NSLS-II RF BPMs) alone or combined with bunch-by-bunch (BxB) data from a BxB feedback system. The single-shot method eliminates the possibility of machine drift and jitter corrupting tune shift measurements. Many more potential applications other than TSwA curve measurements are possible with the setups and diagnostics discussed here. These include single-shot multi-amplitude phase space plotting, simultaneous s-dependent linear and nonlinear lattice characterization, and fast measurements of fine-mesh 1D & 2D DA / TSwA & frequency maps.

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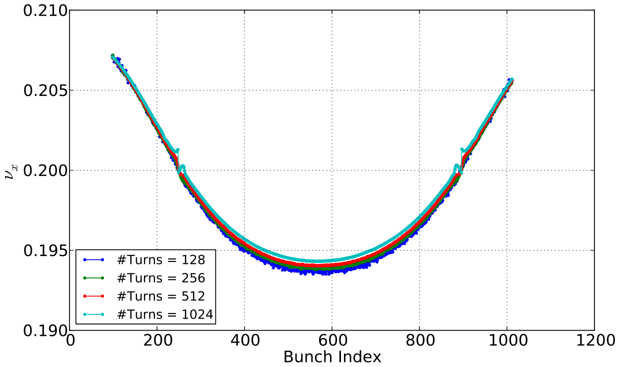

Figure 7: Tune vs. bunch index from single-shot BxB data for a continuous train.

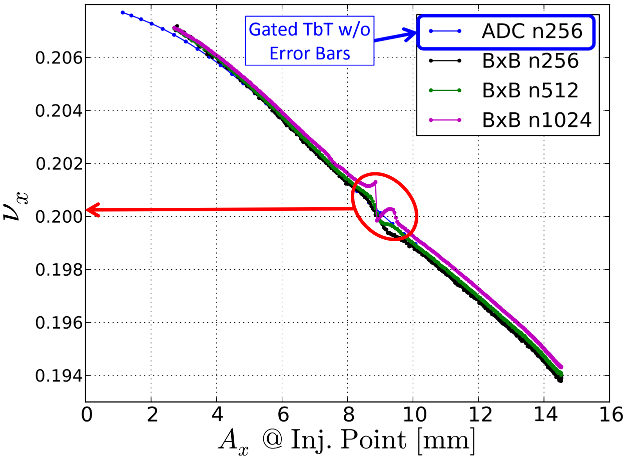

Figure 8: Horizontal TSwA curves from gated TbT alone (blue) and combined with BxB data (256, 512 & 1024 turns used for tune estimate for black, green, magenta). Distortion around $\nu_x = 0.2$ is clear in BxB curves.

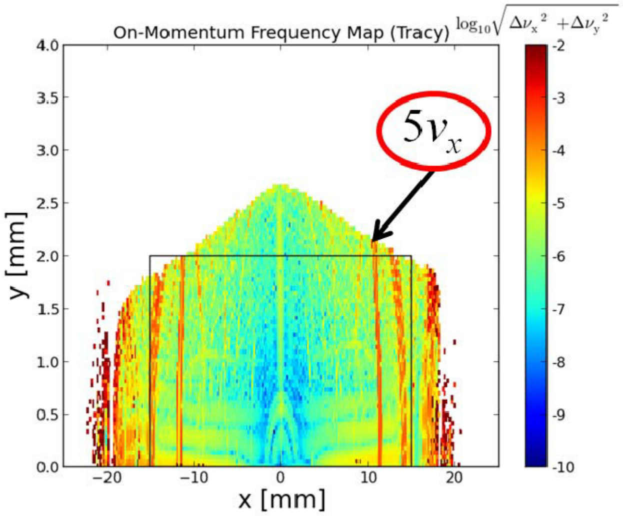

Figure 9: On-momentum frequency map of NSLS-II lattice with 3 damping wigglers closed with random multipole and alignment errors, showing $5\nu_x$ resonance (simulated using Tracy [6]).

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