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Techniques for transparent lattice measurement and correction

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Abstract. A novel method has been successfully demonstrated at NSLS-II to characterize the lattice parameters with gated BPM turn-by-turn (TbT) capability. This method can be used at high current operation. Conventional lattice characterization and tuning are carried out at low current in dedicated machine studies which include beam-based measurement/correction of orbit, tune, dispersion, beta-beat, phase advance, coupling etc. At the NSLS-II storage ring, we observed lattice drifting during beam accumulation in user operation. Coupling and lifetime change while insertion device (ID) gaps are moved. With the new method, dynamical lattice correction is possible to achieve reliable and productive operations. A bunch-by-bunch feedback system excites a small fraction (~1%) of bunches and gated BPMs are aligned to see those bunch motions. The gated TbT position data are used to characterize the lattice hence correction can be applied. As there are ~1% of total charges disturbed for a short period of time (several ms), this method is transparent to general user operation. We demonstrated the effectiveness of these tools during high current user operation.

1. Introduction

Ultra-low emittance is essential for high brightness operation of light sources like NSLS-II. The same is true to achieve high luminosity in lepton collider machines. During NSLS-II operation, betatron tune, coupling and lifetime can be changed while user ID gaps are moved. Orbit disturbance due to the gap movement can be minimized by the feedforward table. However, the tune and coupling variation indicate the lattice is affected by the ID gaps. Besides the ID gaps, there are apparent tune drifts observed with different storage current. This is believed due to the image current effect of flat vacuum chambers and magnet yokes.

Typical lattice characterization and correction are carried out at a low beam current and fixed ID gaps. The corrected lattice isn't reproducible as the ID gaps move and current accumulates. Therefore dynamic lattice measurement and correction are necessary to maintain good machine performance (large dynamic range, long lifetime, good injection efficiency etc.).

There are two types of methods developed to characterize the linear optics. The most common method is Linear Optics from Closed Orbit (LOCO) [1]. Some third generation light sources have used this method to achieve 1pm.rad vertical emittance [2, 3]. At NSLS-II, the more often used method is using BPM turn-by-turn (TbT) data, which is developed based on the original work at LEP [4]. Similar examples can be seen in references [5-7]. Compared to LOCO, the TbT method is much faster. This is especially true for big rings like NSLS-II, equipped with more than 200 BPMs. One iteration of lattice measurement and correction take about 2 minutes [8]. Beta-beat measurement accuracy is ~0.4% from multiple data snapshots. The TbT data has position resolution better than 10μm (7-8 μm for 20-

bunches 1.5mA fill). Two pingers kick the beam within one turn to excite betatron motions in X/Y planes. BPM TbT data acquisition is synchronized with the pinger kicks. Beta-function, phase advance, coupling and other lattice parameters can be measured from one set of BPM TbT data. Corrections can be calculated and applied as needed.

Pinger pulse shape at NSLS-II is about 2μs half sine. To minimize the de-coherence due to bunch to bunch oscillation amplitude difference, only a short bunch train (20-50 bunches) is typically filled. This limits the reliable lattice measurement from TbT data during high current operation when a train of 1000 bunches is filled and bunch to bunch kick amplitude varies.

A new method to characterize the lattice during high current operation is proposed by exciting a small portion of bunches filled in the ion gap and use gated BPM TbT data which measures the betatron motion of those bunches. We refer to those bunches as test bunches. To have a reliable BPM readings, ~1% of total charge is typically filled in the test bunches. See Figure 1 for a typical fill pattern suitable for the new method. With a total beam current of 276mA filled in the ring, the majority of the charge is distributed in the 1000-bunch long train followed by 320 empty buckets to allow ions to escape. Ten bunches were filled in the gap start at bucket #1200, these test bunches had similar per bunch charge as the long bunch train and small bunch to bunch charge variation. Current of the test bunches were ~3.5mA which is ~1.3% of the total storage current of 276mA.

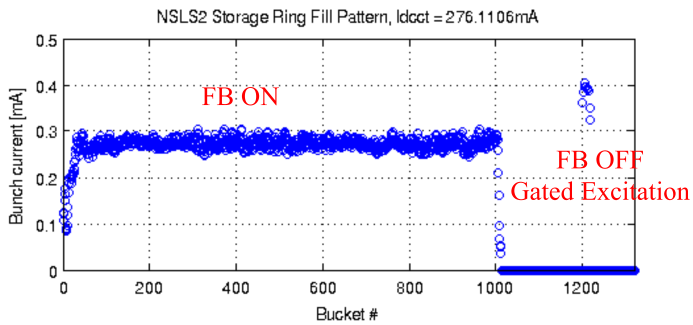

Figure 1. Fill pattern for transparent lattice characterization for 275mA user operation beam.

The 1000-bunch train has transverse bunch by bunch feedback ON to suppress instabilities while the test bunches had feedback OFF. The test bunches were verified to be stable even without feedback. Betatron tune can be measured using any of the test bunches by the integrated function of transverse feedback system, which sweeps across the betatron frequency to see the resonant peak. Once the betatron is known, the test bunches can be resonant excited at this frequency. The excitation is short and is triggered externally. The same trigger is synchronized with BPM gated TbT data which process the test bunches signals.

Digital BPM signal processing expands the capability to select signals from part of the bunches filled in the ring. A similar method has been used during commissioning stage to process the ADC raw data for first turn trajectory and suggested to improve the BPM resolution as discussed in [9]. FPGA firmware has been updated recently to have two different gates that can process the TbT/FA/SA data for different bunches filled in the ring. Timing alignments of the gates are critical to achieve proper processed data.

2. Gated BPM

The NSLS-II in-house developed BPMs incorporate the latest technology available. The same hardware design is used for the LINAC, booster, transfer lines and storage ring. BPM has met the specification and operates reliably for the past years.

The BPM electronics includes mainly two boards: analog front-end (AFE) and digital front-end (DFE). The AFE has band pass filter with center frequency of 500MHz and bandwidth +/-10MHz, this determines the impulse response of ~300ns (~30 ADC samples at 117MHz sampling rate). The DFE board processes the sampled raw ADC data to deliver TbT, 10 kHz and 10 Hz data; the data is then communicated to the control network. Further information of the NSLS-II BPM electronics developments can be found at [10-14].

Because of the +/-10MHz band pass filter and 117MHz sampling rate, NSLS-II BPM electronics are not able to resolve the bunch to bunch positions. However, with bunches separated by more than 300ns, the digitizer is capable to separate signals from those bunches. A typical fill during NSLS-II operation has ~1000 bunches train with bunch separate of 2ns, followed by 320 empty buckets to clear the ions. A signal bunch is filled in the gap for continuous tune measurement and possible single bunch users in the future. Bunch by bunch feedback system is configured to suppress any coupled bunch instabilities in the long bunch train, while keep the test single bunch without feedback.

We propose using the single bunch (or several bunches to improve the signal strength) for lattice measurement. If the BPM signal processing can select the signal only from the bunch(es) in the gap, i.e. to process ADC sampled data with programmable gate, we will be able to measure beam positions from single bunch (or several bunches nearby). The gate function was recently implemented inside the FPGA. Two separate signal processing channels with separate gates are available. Gate delay and gate width can be adjusted so that signal from different bunches can be selected and processed simultaneously. Fine timing alignment (8ns steps) ensures all the BPMs around the ring process the signal from same bunch(es).

Practically the gated bunch(es) shall be ~1% of the total charge so that clean signals can be detected and processed. With the fill pattern in Figure 1, BPM ADC raw data sampled at 117MHz (310 samples per turn) is shown in Figure 2 top image. BPM electronics RF attenuator is set to ~20dB for this current. Four button signals are overlapped as the cables are well matched. With gate, the signal processing will only include the ADC sampled data from bunches in the gap (bottom image).

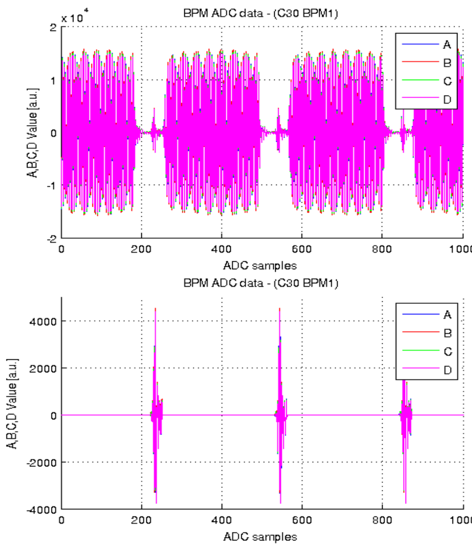

Figure 2. ADC sampled data without gate (top) and with gate (bottom).

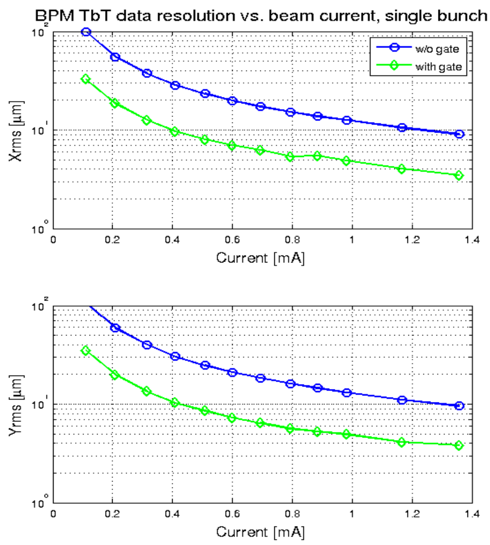

Figure 3. Measured BPM TbT data resolution, with and without gate.

As can be seen from Figure 3, gated BPM TbT data shows ~3 times improvement, compared to the same TbT data without gate. The gate width is set to 30 ADC samples, which improves the signal-noise ratio (SNR) by ~10, the 3 times resolution improvement is proportional to square root of SNR. From Figure 2, the gate width can be further decreased to have better resolution.

3. Bunch excitation

NSLS-II storage ring has transverse bunch-by-bunch (BxB) feedback system installed and commissioned in 2014 [15]. Besides its major function as a feedback controller, the digitizer [16] has extra integrated functions to be used as a powerful diagnostic tool. One such kind of function is the single bunch excitation, which is used at NSLS-II for continuous tune measurement from a test single bunch. Similarly to sweeping tune excitation, the digitizer can drive the beam a single frequency within some pre-defined durations. The transient resonant excitation can be synchronized with external trigger signal so that BPM TbT data will be updated on the same trigger. With proper timing alignment, the feedback digitizer can drive any bunches with frequency near the betatron tune. For bunches to be driven, BxB feedback is turned OFF while the rest of bunches have BxB feedback ON all the time. Bunch to bunch motions are checked with feedback digitizer, during the transient excitation, only test bunches are excited.

BxB feedback station is the only location when bunch to bunch positions can be measured. This is not sufficient to fully measure the machine optics. With bunch(es) filled in the gap with sufficient distance away from other bunches, the normal BPMs are able to separate the signals from the gap bunches, as shown in Figure 2.

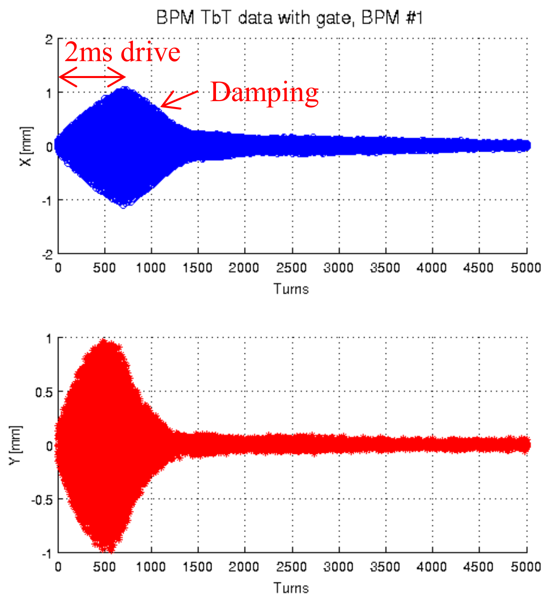

Figure 4. Gated BPM TbT data with bunches in the gap excited to ~1mm peak. The duration of excitation is 2ms.

As described earlier, with proper gates, NSLS-II BPMs around the ring are able to see the bunch motions in the gap. This allows us to measure TbT position of excited bunch(es). The gated TbT data during the free betatron damping can be used to characterize the machine lattice. Figure 4 is gated TbT data with test bunches driven to ~1mm on both planes. The driven signal is switched OFF after 2ms. The test bunches has ~1% of the total charge, it is confirmed from BPM TbT data without gate that there is ~10μm peak oscillation amplitude. The perturbation is much weaker than top-off injection disturbance (~1mm peak amplitude horizontally). As only a very small fraction of bunches oscillate for a short period of time (several ms), we consider this method is transparent to the operational beam.

4. Lattice measurement and correction

Storage ring lattice can be measured from the gated BPM TbT data, even with high current user beam. Figure 5 shows the beta-function measured along the ring. With a well-corrected lattice at low current, beta-beat was increased to 3.9% and 3.4% (X/Y) plane while filling the machine to a higher current and changing ID gaps. It was able to correct to the similar level of ~2% with the gated BPM and CW excitation techniques.

At low current and short bunch train fills, the measured lattice parameters have been compared with the pulse kick and resonant excitation with good agreement.

Phase advance, and linear coupling can also be measured with the same gated TbT data. We observed lattice variation at various beam currents and ID gaps. Applying this technique to study the lattice variation due to collective effects, even to localize impedances, is still under way.

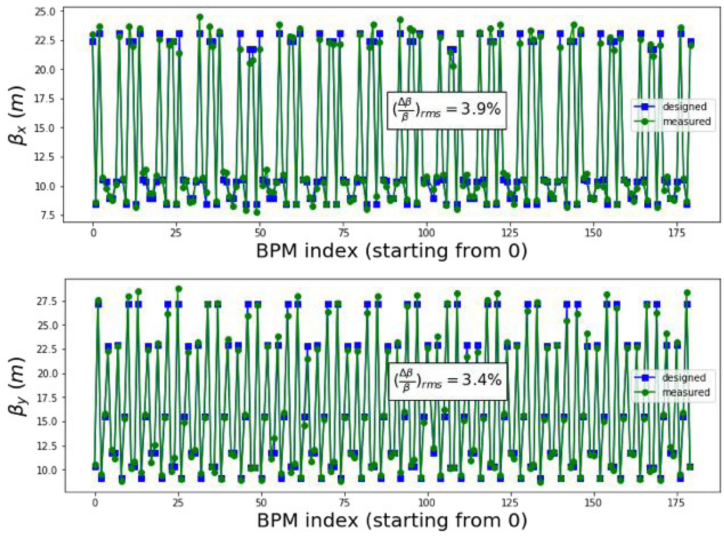

Figure 5. Beta-function measured from gated BPM TbT data. X/Y beta-beat was ~3.9%/3.4%.

5. Summary

New techniques have been proposed and tested to measure the lattice function using gated turn-by-turn data processed from several bunches containing only 1% of the total stored charge. Combine the gated BPM function recently developed at NSLS-II and single bunch excitation function integrated in the BxB feedback system, storage ring linear optics can be measured with little disturbance during high current user operation beam. The method has been successfully tested at NSLS-II storage ring to characterize the lattice and make corrections accordingly. The techniques can be used to study the collective effect and localize the impedances.

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References

[1] Safranek J 1997 *Nucl. Instrum. Methods Phys. Res.* A **338** 27
[2] Aiba M 2012 *Nucl. Instrum. Methods Phys. Res.* A **694** 133
[3] Dowd R 2011 *Phys. Rev. ST Accel. Beams* **14** 012804
[4] Castro P *et al.* 1993 Betatron function measurement at LEP using the BOM 1000 turns facility *Proc. of PAC'93* p 2103
[5] Aiba M *et al.* 2013 *Phys. Rev. ST Accel. Beams* **16** 012802
[6] Franchi A 2016 Error Analysis of linear optics measurements via turn-by-turn beam position data in circular accelerators https://arxiv.org/abs/1603.00281
[7] Alexahin Y, Gianfelice-Wendt E 2011 *Journal of Instrumentation* Vol **6**
[8] Li Y *et al.* 2015 Using big data in NSLS-II storage ring commissioning *Proc. of ICAP2015 (Shanghai China)* p 6
[9] Podobedov B 2016 Single micron single-bunch turn-by-turn BPM resolution achieved at NSLS-

IOP Conf. Series: Journal of Physics: Conf. Series **874** (2017) 012082 doi:10.1088/1742-6596/874/1/012082

II, *Proc.of IPAC'16 (Busan, Korea)* p 2095
[10] Vetter K 2011 NSLS-II RF beam position monitor *Proc. of PAC'11 (New York, USA)* p 495
[11] Vetter K 2012 NSLS-II RF beam position monitor update *Proc. of BIW'12 (Newport News, VA, USA)* p 238
[12] Singh O 2013 NSLS-II BPM and fast orbit feedback system *Proc. of IBIC'13 (Oxford, UK)* p 316
[13] Cheng W 2014 NSLS2 diagnostic systems commissioning and measurements *Proc. of IBIC'14 (Monterey, CA, USA)* p 16
[14] Mead J 2014 NSLS-II RF beam position monitor commissioning update *Proc. of IBIC'14 (Monterey, CA, USA)* p 500
[15] Cheng W 2014 Commissioning of bunch-by-bunch feedback system for NSLS2 storage ring *Proc. of IBIC'14 (Monterey, CA, USA)* p 707
[16] http://www.dimtel.com/