

NOVEL ACCELERATOR PHYSICS MEASUREMENTS ENABLED BY NSLS-II RF BPM RECEIVERS*

Boris Podobedov[#], Weixing Cheng, Yoshiteru Hidaka, Brookhaven National Laboratory, Upton, NY 11973, USA

Dmitry Teytelman, Dimtel Inc., San Jose, CA 95124, USA

Abstract

NSLS-II light source has state-of-the-art RF BPM receivers that were designed and built in-house incorporating the latest technology available in the RF, digital, and software domains. The recently added capability to resolve the orbits of multiple bunches within a turn as well as further improvement in transverse positional resolution for single- and few-bunch fills [1] allowed us to perform a number of novel beam dynamics measurements. These include measuring small impedances of vacuum chamber components, and of extremely small ($\sim 1e-5$) current-dependent tune shifts, as well as obtaining an amplitude-dependent tune shift curve from a single kicker pulse.

In this paper we briefly review the unique capabilities of NSLS-II BPMs and present examples of beam physics measurements that greatly benefit from them.

INTRODUCTION

NSLS-II is a recently constructed 3 GeV synchrotron light source at the Brookhaven National Laboratory presently in routine operations for a growing user community. By design, the vertical beam size at NSLS-II could be as low as 3 microns RMS, so a very significant effort went into ensuring that orbit stability is guaranteed to be a small fraction of that. To that extent state-of-the-art RF BPM receivers were designed and built in-house [2-8]. Among many challenging BPM specifications the key ones are related to the resolution and long term stability. The BPMs were commissioned some time ago and all of the design specifications have been confirmed with beam. Reaching turn-by-turn (TbT) resolution of 1 μm and 200 nm for 10 kHz sampled orbit was reported in [4], for measurements with long bunch trains (NSLS-II user operations typically run with ~ 1000 bunches filling consecutive 500 MHz RF buckets; harmonic number is 1320).

However, with the standard BPM signal processing the resolution for single bunch fills is a lot lower, i.e. $\sim 10 \mu\text{m}$ TbT at 0.5 mA [4]. Also, standard processing does not resolve the positions of individual bunches within a turn. Since better single-bunch resolution as well as the ability to measure TbT positions of at least a few bunches stored in the ring is strongly desired for some sensitive beam dynamics experiments we have recently addressed both of these issues by special BPM signal processing [1].

Briefly, intra-turn capability was achieved by separately processing fractions of BPM button ADC samples acquired on every turn, with each fraction timed to the

bunch of interest. This also provided some resolution improvement for single- and few-bunch fills. Additionally resolution was improved by including multiple revolution harmonics in the TbT position calculation. With this new BPM signal processing we can resolve up to 8 bunches stored in the ring, essentially limited by the bandwidth of the BPM front-end filter that stretches the FWHM duration of a single bunch pulse to ~ 20 ADC samples out of the total of 310 acquired every turn. The resolution improvement for single bunch fills was about one order of magnitude, down to $\sim 1 \mu\text{m}$ TbT at 0.5 mA.

BEAM PHYSICS MEASUREMENTS

The ability to resolve multiple bunches within a turn combined with improved BPM resolution allowed us to carry out a number of novel beam physics measurements. Here we concentrate on the measurements of small relative tune shifts and the related ones for transverse coupling impedances. More are described in the accompanying IBIC'16 talk and in [1].

Small Relative Tune Shifts

The standard way of measuring betatron tunes is by exciting the beam with a pinger magnet. At NSLS-II this measurement is usually done with a short, low current bunch train, typically 1-2 mA in 100 consecutive buckets. TbT positions are recorded on 180 regular RF BPMs around the ring. The data from each BPM is processed individually to obtain 180 tune values. Their average gives the final measured tune while their RMS spread provides the measurement error. If a large number of turns is processed, we typically find that, for each individual measurement, the final tune value could be resolved to better than $1e-6$.

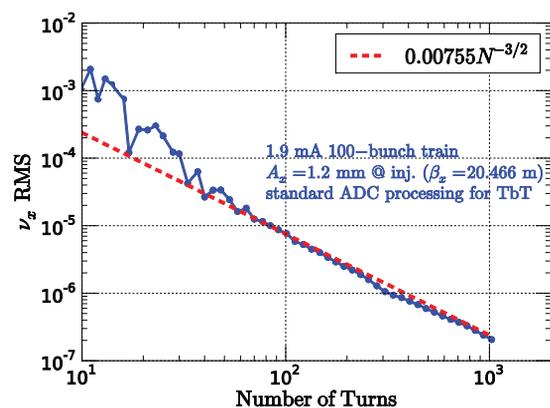


Figure 1: RMS of horizontal tune vs. number of turns.

* Work supported by DOE contract DE-AC02-98CH10886.

[#] boris@bnl.gov

Figure 1 presents a measurement, taken after a single horizontal ping with the total of 1000 TbT positions recorded. For each BPM the tune was found by the interpolated FFT method with DFT fine-tuning, and by processing only the first $N \leq 1000$ turns. RMS of these 180 tunes vs. N , plotted in Fig. 1, converges well to the expected [10, 11] asymptotic scaling $\sim N^{-3/2}$.

For the number of turns approaching one thousand the tune measurement error is $\sim 2e-7$ (RMS). Thus, over short timescales (1000 turns is 2.64 ms), the tune is very stable and could be measured with very good accuracy.

Unfortunately conventional beam physics measurements that require varying the bunch charge, or other parameters, cannot directly benefit from this, because over longer timescales, required for any parameter variation, the tunes are much less stable. For instance, repeated pinger measurements, performed at 20 second intervals, result in shot-to-shot tune jitter at the level of few times $1e-4$ or more. Similar levels of tune stability are confirmed with the bunch-by-bunch feedback system that uses entirely different hardware and algorithms for tune measurement [9].

Our new method, however, allows one to overcome the limitations coming from the tune jitter. Recording and processing TbT positions of two (or more) simultaneously stored bunches of different charge, we can keep taking advantage of very good tune stability over short timescale.

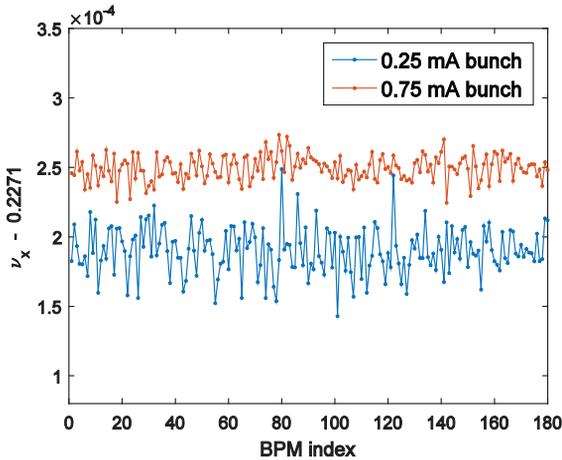


Figure 2: Horizontal tunes of two stored bunches.

This is illustrated in Fig. 2, showing the result of horizontal tune measurement with two bunches, of unequal charge, stored in the ring diametrically opposite to each other. The pinger magnet timing was adjusted to provide equal kick to both bunches. 100k-sample ADC data buffers (i.e. ~ 320 turns), triggered on a ping, were recorded for 180 regular BPMs. The 100-sample-long boxcar windows, centered on the bunches, were applied before the TbT positions for each bunch were calculated using 25 revolution harmonics (maximum number within the bandwidth of the so-called “pilot tone filter” [7], ON at the time). Performing a statistical analysis for 180 BPMs we obtained $\nu_x = 0.22729 \pm 1.71e-05$ (0.25 mA bunch) and

$\nu_x = 0.22735 \pm 9.06e-06$ (0.75 mA bunch), with \pm numbers indicating one standard deviation.

The resulting tune difference was $\Delta\nu_x = (6.0 \pm 1.9) \cdot 1e-5$, proving that even for as few as $N=300$ turns we can comfortably resolve the tunes of two bunches to the level much lower than the few times $1e-4$ typical tune stability.

Even without increasing single bunch currents this relative tune resolution could be improved further by 1) increasing the number of turns; 2) using a short low current train such as one used for Fig. 1 as a “low charge per bunch reference” as opposed to using a single bunch; and 3) further increasing the number of revolution harmonics used for TbT position calculations up to ~ 50 to match the front-end filter bandwidth (possible when “pilot tone filter” is off). Scaling from currently available data we believe that tune resolution of $\sim 1e-6$ RMS should be reachable.

Furthermore, since the relative measurement is performed, this resolution should be preserved over a much longer timescale than that of the individual measurement. This is because the most likely sources of the short term tune drift (quadrupole PS noise, RF frequency noise plus non-zero chromaticity, etc.) are affecting the reference and the high current bunches by the same amount. Thus precise repeated measurements, while varying the bunch charge or other parameters should be possible.

Impedance from Relative Tune Shifts

The ability to measure relative tunes of unequal charge bunches with good precision is immediately applicable to the measurement accuracy of transverse coupling impedances, $Z_{x,y}(\omega)$, or kick factors, related to the impedances by $k_{x,y} \propto \int \text{Im}[Z_{x,y}(\omega)] |\tilde{\rho}(\omega)|^2 d\omega$, where $\tilde{\rho}(\omega)$ is the Fourier transform of the longitudinal beam density. The kick factors determine current-dependent tune shifts,

$$\delta\nu_{x,y}(Q) = -k_{x,y} Q \frac{\langle \beta_{x,y} \rangle}{4\pi E / e}, \quad (1)$$

due to an impedance-carrying vacuum chamber component with the average beta functions $\langle \beta_{x,y} \rangle$, where Q and E are the bunch charge and energy. Denoting the low-current reference bunch and the high-current bunch by corresponding subscripts we get for the kick factor,

$$k_{x,y} = \frac{4\pi (\nu_{x,y-ref} - \nu_{x,y-hi}) E / e}{(Q_{hi} - Q_{ref}) \langle \beta_{x,y} \rangle}. \quad (2)$$

For example, if, for the charge difference of 1 nC we are able to resolve the tune difference of $1e-6$, then, at 3 GeV and taking a 4 m beta function, we could measure kick factors as low as 10 V/pC/m. In the vertical plane such a kick factor would be equal to that due to the resistive wall of an Al vacuum chamber pipe with 12 mm vertical aperture that is only one meter long! (we assumed elliptical cross-section with large horizontal-to-vertical aspect ratio and a 5 mm RMS Gaussian bunch typical for NSLS-II). Clearly, the ability to resolve impedance components as small as this would be highly desirable.

Of course, machine tunes are global quantities, so generally one cannot attribute the tune shifts in (2) to a par-

ticular impedance component. However, for the components with controllable geometry (in-vacuum undulators, scrapers, etc.) the impedance they present to the beam can be changed, and therefore easily isolated. For fixed impedance components, similarly to [13], this isolation could be achieved with local bumps.

We illustrate this method with the measurement of one of the NSLS-II vertical scrapers, which essentially consists of two 1 cm thick and 3 cm wide vertically movable rectangular blades made of Cu. The measurement was done with a 100 consecutive bucket train of 1.4 mA total current plus a 0.3 mA camshaft bunch stored in an RF bucket $\frac{1}{2}$ the ring circumference away from the train. Both were kicked to the same amplitude with a vertical pinger, while ~ 900 turns worth of ADC data for 180 BPMs were recorded, and then processed, with ADC windows, to get the tunes. Several measurements like this were taken as the top scraper blade was moved closer to the beam. In Fig. 3 one can see a significant increase in the relative tune shift as the scraper impedance becomes more and more dominant. From (2) the total tune shift in Fig. 3 of $\sim 3e-4$ corresponds to the kick factor of ~ 600 V/pC/m (β_y at the scraper location is 26 m). As expected the kick factor is quite high, and detailed comparison with the impedance models is in progress. Note, however, that the error-bars in Fig. 3 are on the order of $3e-6$, giving us confidence that much smaller kick factors are measurable with this method.

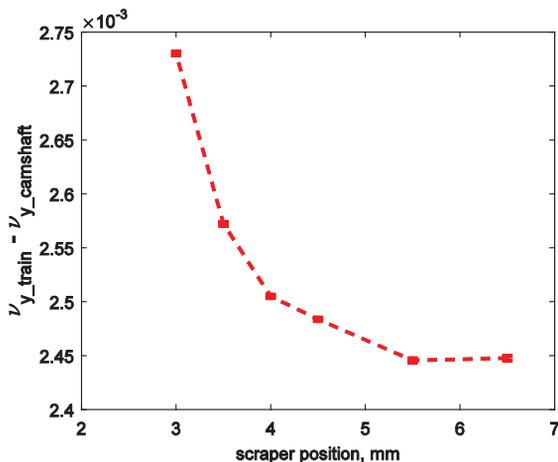


Figure 3: Relative tune shifts due to vertical scraper.

We now present preliminary results for a much more challenging ring component, specifically an (out-of-vacuum) undulator chamber in a low- β (cell 21) ID straight of NSLS-II. This chamber is 4.8 m long Al pipe with 60×11.5 mm² elliptical cross-section. Gradual tapered transitions to a larger cross-section as well as some other components are located on both sides of this chamber, but the resistive wall impedance is expected to dominate. Unlike the scraper, the chamber impedance is fixed, so impedance localization was done with local bumps. Specifically, we applied vertical bumps that created parallel displacement in the 21ID straight and virtually no orbit perturbation elsewhere. We used the same fill pattern as

the one for the scraper measurement above. The tune difference was measured, in order, for -4 mm bump, without the bump, and then with 4 mm bump (see Fig. 4).

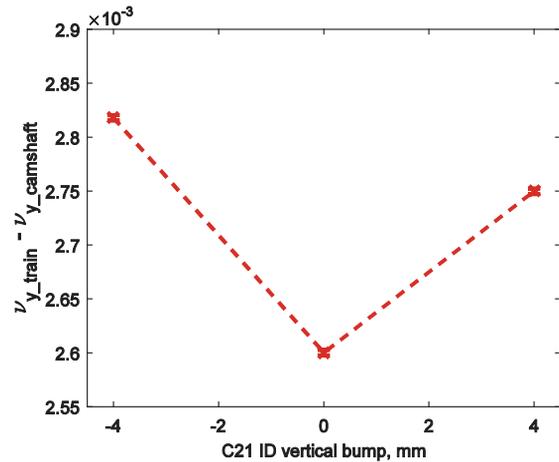


Figure 4: Relative tune shifts with local bumps in C21 ID.

Some asymmetry in the tune shifts is evident. We attribute most of it to some charge loss in the camshaft bunch during the measurement as well as to the bump imperfection. Still, averaging the tune shifts from the positive and negative bumps we can estimate the kick factor for a 4 mm vertically displaced beam from (2). To get the kick factor for the beam centered through chamber we use the well-known resistive wall expressions from [13] and get ~ 210 V/pC/m ($\langle \beta_y \rangle$ is 2.84 m). This is significantly higher than the 56 V/pC/m resistive wall kick factor one calculates for this chamber assuming pure Al and a separately measured bunch length of 16.2 ps at 0.3 mA. Note however, that the actual chamber is NEG coated with nominal layer thickness of 1 μ m, which could explain some if not most of this discrepancy. Further investigation is ongoing.

Other Methods of Impedance Measurement

So far we focused on impedance measurements with kicked beams that rely on precise measurements of relative tune shifts. While we believe this method holds a lot of potential, we emphasize that many other methods would benefit from simultaneous measurements of unequal charge bunches because this reduces the effects of machine drifts. For instance, the resolution of the local bump method for measurements of the effective impedance from closed orbits of low and high charge bunches [12] is limited by closed orbit drifts. If, however, the orbits of high and low charge bunches are measured simultaneously, the resolution could be significantly improved. While so far we have not explored this due to size limitations for ADC data buffers available for off-line analysis, we will use this technique as an independent cross-check when closed orbits of multiple bunches are implemented in FPGA and are available through EPICS.

Measurements of Tune Shift with Amplitude

Another technique that became available with new BPM capabilities is a single-shot measurement of amplitude-dependent tune shift curve. This time bunches of equal charge need to be kicked to different amplitudes, which is accomplished by placing them at the different amplitude locations along the kicker waveform. Furthermore, this measurement does not require resolving the tunes of individual bunches but only the tunes of groups of bunches kicked to the same amplitude. This is why bunch separation is unnecessary, so the measurement is presently performed with a long bunch train overlapping with the rising portion of the kicker pulse. This single shot technique allows one to overcome tune jitter limitations, and it favourably compares to the multi-shot, conventional method. This is further illustrated in the accompanying talk and in [1].

SUMMARY AND FUTURE WORK

Single-bunch resolution of NSLS-II BPMs was recently improved by an order of magnitude to about one micron TbT at ~ 1 nC/bunch. This improvement was achieved through special processing of ADC signals which additionally provides the new capability of resolving TbT signals from several bunches stored in the ring. Having this capability on all NSLS-II RF BPMs is extremely valuable for sensitive collective effect or single particle dynamics measurements. It allows us to simultaneously measure bunches with different charges (or kick amplitudes) thus eliminating harmful effects of machine drifts.

We presented some novel accelerator physics measurements enabled by these new BPM capabilities. These include a new technique of probing the ring impedance by measuring relative tune shifts between the bunches of unequal charge. This technique is very accurate because it takes advantage of extremely good tune stability over very short timescales thus allowing to resolve relative tunes to the level of $1e-5$ or better. Another novel technique is a single-shot measurement of amplitude-dependent tune shifts. More studies are in progress. We presently believe that many of them could greatly benefit from including additional diagnostics available through the bunch-by-bunch feedback system.

ADC signal processing that resolves the orbits of multiple bunches within a turn has been so far done off-line. It is presently being implemented in FPGA, so that improved positional resolution and multi-bunch capability will be available in real time through EPICS and the present limitation on data buffer length of 3.2 k-turns of TbT data (1 million ADC samples) will no longer apply. This will allow us, for example, to analyze the individual closed orbits of multiple stored bunches vastly expanding our toolkit for studying beam dynamics at NSLS-II.

Finally, we would like to acknowledge the enormous help we received from many of our NSLS-II colleagues but especially from Kiman Ha, Joe Mead, Om Singh and Kurt Vetter (presently at ORNL).

REFERENCES

- [1] B. Podobedov *et al.*, "Single Micron Single-Bunch Turn-by-Turn BPM Resolution Achieved at NSLS-II," IPAC'2016, pp. 2095-2098.
- [2] K. Vetter *et al.*, "NSLS-II RF Beam Position Monitor", PAC'2011, pp. 495-497.
- [3] K. Vetter *et al.*, "NSLS-II RF Beam Position Monitor Update", BIW'2012, pp. 238-241.
- [4] W. Cheng *et al.*, "Characterization of NSLS2 Storage Ring Beam Orbit Stability", IBIC'2015, pp. 625-629.
- [5] W. Cheng, B. Bacha, O. Singh, "NSLS2 Beam Position Monitor Calibration", BIW'2012, pp. 77-79.
- [6] W. Cheng *et al.*, "Performance of NSLS2 Button BPMs", IBIC'2013, pp. 678-681.
- [7] O. Singh *et al.*, "NSLS-II BPM and Fast Orbit Feedback System", IBIC'2013, pp. 316-322.
- [8] J. Mead *et al.*, "NSLS-II RF Beam Position Monitor Commissioning Update", IBIC'2014, pp. 500-504.
- [9] W. Cheng *et al.*, "Commissioning of Bunch-by-Bunch Feedback System for NSLS2 Storage Ring", IBIC'2014, pp. 707-711.
- [10] R. Bartolini *et al.*, "Precise Measurements of the Betatron Tune", Part. Accel. 55, 1 (1996).
- [11] N. Biancacci and A. Thomás, "Using AC Dipoles to Localize Sources of Beam Coupling Impedance", Phys. Rev. Accel. Beams 19, 054001 (2016).
- [12] V. Kiselev, V. Smaluk, "A Method for Measurement of Transverse Impedance Distribution along Storage Ring", DIPAC 1999, pp. 202-204.
- [13] A. Piwinski, "Wake Fields and Ohmic Losses in Flat Vacuum Chambers", DESY HERA 92-04 (1992).