SINGLE MICRON SINGLE-BUNCH TURN-BY-TURN BPM RESOLUTION ACHIEVED AT NSLS-II*

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Abstract

NSLS-II state-of-the-art BPMs provide a single micron turn-by-turn resolution for any bunch train of reasonable intensity. For certain beam dynamics studies a similar, or even better, resolution is desired for a single-, or a few-bunch fill, which is not yet available with our standard BPM signal processing. This paper describes our experience with more advanced BPM ADC signal processing which allowed us to significantly improve turn-by-turn BPM resolution in single bunch mode down to the level of about one micron at ~1 nC/bunch. We also present the examples of machine studies that benefit from this BPM performance enhancement.

INTRODUCTION AND MOTIVATION

NSLS-II is a recently constructed synchrotron light source at the Brookhaven National Laboratory presently in routine operations for a growing user community [1].

NSLS-II design vertical emittance of 8 pm results in the vertical beam size as low as 3 µm at the centers of low-β insertion device (ID) straights. This, together with strict requirements on orbit stability, has resulted in very challenging specifications for BPM resolution. To meet these, state-of-the-art NSLS-II RF BPM receivers were designed and built in-house incorporating the latest technology available in the RF, Digital, and Software domains [2-3].

NSLS-II storage ring BPMs were commissioned some time ago and all of the design specifications have been confirmed with beam. In particular reaching turn-by-turn (TbT) resolution of 1 µm was reported in [4]. This resolution is routinely available for long bunch trains of reasonable intensity (i.e. >10 mA for 1000 bunch trains).

For single bunch fills, typically done at a much lower current, the best resolution with our standard BPM signal processing is 1-2 orders of magnitude lower, i.e. ~10 µm at 0.5 mA [4]. A better resolution is strongly desired for sensitive beam dynamics experiments which include collective effects, impedance measurements, single particle nonlinear dynamics and beam lifetime studies, especially in cases when small effects could be masked by machine drifts. Also needed is the ability to measure individual TbT positions of at least a few bunches (or groups of bunches) stored in the ring. This option is not presently available with our standard BPM signal processing.

This paper describes our approach to improve BPM resolution for single bunch fills, as well as to add the capability of resolving several bunches within a turn.

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RESOLUTION IMPROVEMENT

Out of several NSLS-II storage ring RF BPM types the most numerous are 180 “regular” BPMs located on multipole girders and mounted on large-aperture (LA) vacuum chambers. There are also ID BPMs (2-3 per ID straight, presently ~30 total), located on small-aperture (SA) ID chambers. The geometry difference results in a factor of ~2 better sensitivity and resolution for ID BPMs, which is useful since their locations correlate with the smaller electron beam size.

NSLS-II RF BPM receiver is described in [2-8]. BPM button signals are sampled by BPM ADCs 310 times per ring revolution (at ~117 MHz). The revolution frequency, Frev, is 1/1320 of the 500 MHz RF frequency.

BPM resolution, in each plane, is defined as the rms of TbT positions taken over a few thousand turns (2.9k in this paper). To exclude the effects of beam motion a combiner-splitter setup was implemented on a test LA BPM in cell 28. An RF signal from each BPM button is equally split with a 3-dB splitter. One branch is connected to a BPM receiver the usual way to measure the transverse position. The other branch has the 4 button signals summed with a 4:1 combiner. Then the summed signal is split using a 1:4 splitter connected to the 4 input channels of the combiner-splitter BPM receiver (BPM 28-9). Neglecting the insertion loss of other components, the 3-dB splitters degrade the resolution of the combiner-splitter BPM by a factor of √2 compared to a regular LA BPM.

A typical raw ADC signal with a single bunch stored in the ring is shown in Fig. 1. The pulse shape is defined by two band-pass filters, the 500 MHz analog front-end one (bw~20 MHz) and the so-called digital “pilot-tone filter” (bw~6 MHz, applied right at the ADC output). The pilot tone filter can be turned off during machine studies.

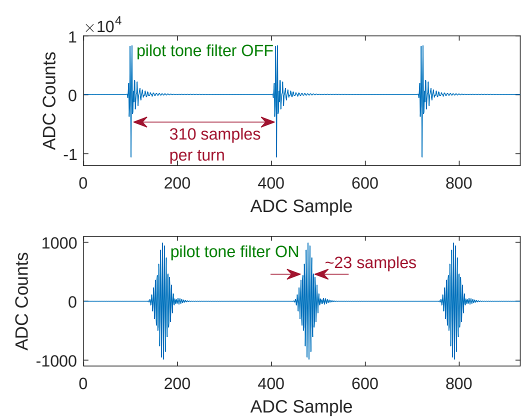

Figure 1: 3 turns of raw ADC data; 0.5 mA single bunch.

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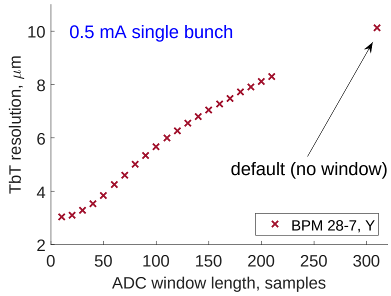

Figure 2: Resolution vs. ADC signal window length.

As is clear from Fig. 1 for single bunch fills the majority of the ADC samples contain no beam signal and are dominated by noise. Setting these samples to zero, i.e. applying, on every turn, a boxcar window centered on the bunch prior to calculating the TbT positions, results in the resolution improvement factor of 3-4 as is shown in Fig. 2 for one of the ID BPMs.

Another approach to improve BPM resolution in the single bunch mode is to include multiple revolution harmonics in the TbT position calculation. The standard processing, implemented in FPGA, looks only at a single revolution harmonic, f = 1320 Frev, which is adequate for long trains used in user operations. In the single bunch mode, including ~25 harmonics improves the resolution by about a factor of 4 before one is limited by the pilot-tone filter. With this filter off the number of harmonics can be further increased to improve the resolution by a factor of ~7, limited by the front-end filter bandwidth.

Figure 3 shows that increasing the number of revolution harmonics used in TbT position calculation up to ~70 brings the directly measured TbT resolution for a typical ID BPM down to 1.7 µm at 0.5 mA single bunch. This is an upper estimate of the resolution as it includes some contribution from beam motion. The data taken simultaneously on the combiner-splitter BPM show that resolution improves from 36 to ~5 µm. Scaling this number by the sensitivity ratio between the LA and SA chambers and accounting for 3 dB power loss in the combiner-splitter setup we obtain the vertical resolution for ID BPMs to be about 1.3 µm at this current. The horizontal resolution is a factor of ~2 larger due to the chamber geometry.

The frequency- and time-domain resolution improvement techniques can be combined, as well as applied to the fills with multiple bunches. One can select a particular bunch by ADC windowing described above, include enough revolution harmonics, calculate the TbT positions, and then repeat the process for the remaining bunches.

Of course the TbT positions calculated for individual bunches are meaningful only if these bunches are well separated. From the data shown in Fig. 1 (bottom) we estimate that 99% of single bunch signal power, ~(ADC count)^2, is contained within 40 ADC samples around the bunch center. Therefore, for a symmetric 8-bunch fill, such a window contains ~1% contamination from the neighbouring bunches, which is tolerable for most experiments. In case of unequal charges or bunch spacing, the maximum number of resolvable bunches is lower, but likely still adequate for most beam physics experiments.

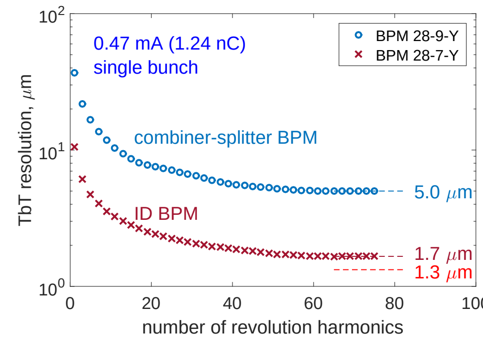

Figure 3: Resolution vs. number of revolution harmonics.

BEAM PHYSICS BENEFITS

The ability to resolve multiple bunches within a turn combined with improved resolution, allowed us to carry out a number of novel beam physics measurements. Here we report on two that best demonstrate new BPM capabilities. Due to space constraints only the key steps are illustrated below. More details are available in the accompanying IPAC'16 talk.

Current-dependent Tune Shift

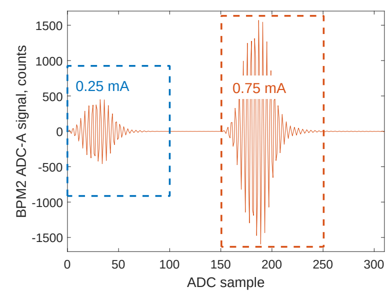

Figure 4: One-turn ADC signal for two-bunch fill.

For this measurement we stored two bunches, 0.25 and 0.75 mA, in two RF buckets diametrically opposite to each other. A typical ADC signal is shown in Fig. 4.

The vertical pinger magnet timing was adjusted to provide equal kick to both bunches. 10k-sample ADC data buffers, triggered on a ping, were recorded for 180 regular BPMs. The 100-sample-long boxcar windows, sketched in Fig. 4, were applied before the TbT positions for each bunch were calculated by a standard algorithm.

The resulting TbT positions, at a single BPM, are shown in Fig. 5. Also plotted is the position calculated for the entire 2-bunch fill obtained by the default signal processing algorithm that uses all 310 ADC samples per turn.

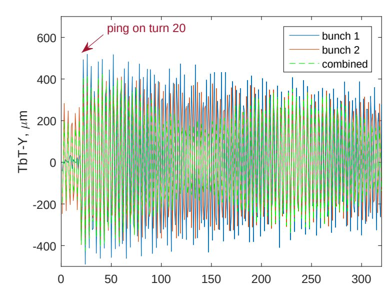

Figure 5: TbT signals of unequal bunches after a ping.

Prior to the ping, the higher intensity bunch undergoes some betatron oscillations. This is due to a vertical instability (TMCI), separately confirmed to set in at a slightly lower single bunch current. This illustrates the power of this technique for instability diagnostics.

The FFT of the signals shown in Fig. 5 clearly shows a lower tune for the higher intensity bunch, see Fig. 6.

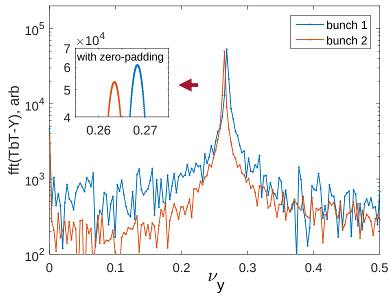

Figure 6: Tunes obtained from the data shown in Fig. 5.

More advanced techniques such as interpolated FFT allow one to resolve the tunes with better accuracy. Performing a statistical analysis for 180 BPMs we obtained ν_y=0.26833 ±1.93e-5 (bunch 1) and ν_y=0.26334 ± 6.90e-6 (bunch 2), with ± numbers indicating one standard deviation. The resulting approximately -0.01/mA tune slope is consistent with that measured by other methods [9, 10].

While the above measurement can be easily done with other techniques, the same experiment in the horizontal plane is a lot more challenging, simply because the tune slope is orders of magnitude smaller [10]. We repeated the experiment for the same fill pattern but using the horizontal pinger. The resulting tune difference was $\Delta\nu_{x21}$= (6.0 ± 3.8)*1e-5, suggesting that the higher intensity bunch has a higher horizontal tune. However the uncertainty was rather large and a few BPMs have even indicated the opposite sign of the tune slope.

We then applied the frequency-domain resolution improvement technique to the same data. Including 25 revolution harmonics improves the resolution by an estimated factor of 4, thus allowing us to determine the tunes more accurately. Indeed, the final result was $\Delta\nu_{x21}$=(6.0 ± 0.9)*1e-5, i.e. the uncertainty was reduced by a factor of 4; so we could confidently state that the horizontal tune increases with current. This clearly illustrates how BPM resolution improvement benefits these types of beam physics measurements.

Tune Shift with Amplitude

This measurement is important for understanding nonlinear single particle dynamics. It is usually done at low current (to limit collective effects) and with short bunch trains, placed near the peak of pinger pulse (at NSLS-II its FWHM is ~0.6/Frev). Data is collected for multiple pinger pulses set for different kick voltage. When amplitude-dependent tune shifts are small, shot-to-shot jitter and machine drifts make this measurement quite challenging.

Our new ADC processing technique allows making the entire measurement with a single pinger pulse, thus eliminating detrimental effects of machine drifts. This measurement is performed with a long bunch train timed to overlap with a rising portion of the pinger pulse. Different bunches experience different kick amplitudes, and, by applying appropriately timed windows to the collected BPM ADC data we can separately process groups of bunches kicked to different amplitudes. This works, as long as the windows are shorter than the pinger rise time.

Horizontal tune shift with amplitude obtained with this new, single shot technique is shown in Fig. 7. A 2-kV pinger pulse was applied to a uniform 1000 bunch train with 5 mA total current, while ADC data was recorded. For post-processing, 11-sample-long ADC window was shifted, one sample at a time, through the portion of the bunch train overlapping the rising part of the pinger pulse. For each window position (total ~150) a TbT data set was calculated from the windowed ADC data and then processed to extract amplitudes and tunes with the error-bars coming from the spread among the 180 BPMs used (see the talk for intermediate steps).

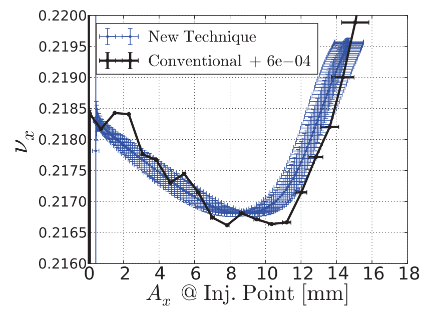

Figure 7: Horizontal tune shift with amplitude.

The resulting curve is very smooth and is shaped in qualitative agreement with theory. This result favourably compares to the one obtained via a conventional technique, shown in black, taken with 20 separate pinger pulses (the data for both curves was taken within a minute of each other). That technique clearly suffers from significant pulse-to-pulse jitter and likely also from longer term machine drifts. While the conventional method was already optimized in numerous machine studies, further optimizations of the new technique are foreseen.

CONCLUSION

Single-bunch resolution of NSLS-II BPMs was 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 up to 8 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.

ADC processing is presently done off-line but will be implemented in FPGA, so that improved resolution will be available through EPICS. Novel accelerator physics measurements enabled by improved resolution and new BPM capabilities will continue.

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