Method Article

Beam position monitor gate functionality implementation and applications

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A B S T R A C T

We introduce a novel technique to implement gate functionality for the beam position monitors (BPM) at the National Synchrotron Light Source II (NSLS-II). The functionality, now implemented in FPGA, allows us to acquire two separated bunch-trains' synchronized turn-by-turn (TBT) data simultaneously with the NSLS-II in-house developed BPM system. The gated position resolution is improved about 3 times by narrowing the sampling width. Experimentally we demonstrated that the machine lattice could be transparently characterized with the gated TBT data of a short diagnostic bunch-train Cheng et al., 2017; Li et al., 2017. Other applications, for example, precisely characterizing storage ring impedance/wake-field through recording the beam positions of two separated bunch trains has been experimentally demonstrated.

- Gated BPM signal processing improves the position resolution.
- Transparent lattice measurement using the gate function with diagnostic bunches.
- Collective effect study with simultaneous position measurement from two gates.

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Method details

Introduction

The NSLS-II in-house developed BPM [3–5] adopts bandpass sampling theorem [6] for precise beam position measurement, similar to other modern BPM electronics. The BPM provides various beam position data acquisition for the routine operation and machine studies. Raw analog-to-digital (ADC) data is typically used for single pass (or first turn) measurement and BPM timing alignment; turn-by-turn (TBT) data processed from 310 ADC samples (for the NSLS-II storage ring) is widely used for physics studies; ~10 kHz fast acquisition (FA) data, further decimated from TBT data, is used for fast orbit feedback and active interlock for machine protection; 10 Hz slow acquisition (SA) data is typically used for closed orbit measurement and is streaming out through control network. FA data is well suited to study the performance of orbit stability within the range of 1 Hz to ~kHz. FA data is shared around the ring through cell controllers and serial data interface (SDI) fiber link with low latency.

In storage rings, the beam-induced signal on the button BPM contains harmonics of the bunch revolution frequency (RF frequency if all buckets are evenly filled). BPM electronics typically works at one of these harmonics below the chamber cutoff frequency, to eliminate possible high-order mode signals. The button signal has a pulse width of ~100 ps, which depends on bunch length, button capacitance, and cable attenuation. A low pass filter is used to remove the high-frequency components of the button signal. Similar to many other light sources, the NSLS-II ring has RF frequency at 500 MHz, the BPM electronics was designed to detect the button signal at the 1st harmonic of RF frequency. As illustrated in Fig. 1, which includes major components of BPM system before the digitizer, a bandpass filter (BPF) has ±10 MHz bandwidth with a center frequency of 500 MHz. The BPF broadens BPM button signal to ~200 ns. Amplifiers and attenuators are added to further condition beam signals to a large dynamic range for various beam currents and filling patterns. A 16-bit ADC digitizes the signal for digital signal processing, 310 times per revolution period. Typical fill pattern during operation has ~80% buckets filled out of 1320, therefore the majority of the ADC samples in one turn includes beam position information. However, during machine development or studies, the beam is typically filled with a short bunch train or single bunch. In this case, the beam-induced signal appears on a small fraction of 310 ADC samples in one turn, as shown in Fig. 1 which plots the ADC data with two bunch

![Diagram](image-url)

**Fig. 1.** Schematic diagram of major analog signal conditioning blocks for the NSLS-II BPM electronics. The embedded plot shows the ADC raw data after the digitizer with two bunch trains filled in the ring. The first train had ~3.9 mA filled in 150 consecutive buckets, while the second train had 3.1 mA evenly distributed in 10 bunches, with ~20 ns bunch separations. Two gates were applied to process the beam positions of the two bunch trains as demonstrated in the shaded area.
trains filled in the storage ring. A gated process of ADC data with only beam signal included helps to improve the signal-to-noise ratio, hence the position resolution is improved significantly, especially for short bunch train fills.

The gate functionality has been considered when the BPM system was designed and used to process the first turn data during the early commissioning stage of NSLS-II. Improvement in BPM resolution by means of gated processing of BPM ADC data was demonstrated in [7]. Meanwhile, with multiple gated signal-processing channels, simultaneous measurements of machine parameters (like betatron tune, lattice functions, and collective effects) from different bunch-trains are possible [8]. Thus far, due to the limitation of our existing FPGA (field programmable gate array) resources, two signal-processing channels with gates are implemented in all storage ring operating BPMs. More gates are possible with the new digital processing board under development, which will have more FPGA resources.

To summarize, the motivation for this work is to demonstrate the real-time gated processing realized at NSLS-II storage ring BPMs, and report several measurements with the gates. This paper is structured as follows. Implementation of the gated signal processing and timing alignment will be discussed in Section implementation of gate functionality. Various beam measurements with the gate functionality are presented in Section measurements. In Section discussion and future developments, we further discuss possible developments of BPM gate function and BxB position measurement.

**Implementation of gate functionality**

As mentioned earlier, when a short bunch train is filled in the ring, the beam-induced signal appears on a small fraction of ADC digitized waveform within a turn. By selecting and processing the beam induced signal, the TBT positions will have improved resolution. We refer to this selected beam signal processing as gate function. There are two identical signal processing channels with gates implemented in the NSLS-II storage ring BPMs. The gate width and delay are programmable with ~8 ns steps, which is the ADC sampling period.

The first channel has been modified based on the existing signal processing chain, by adding a gate to process the selected ADC data. As shown in Fig. 2, following the ADC, digitized data is processed inside the FPGA. Digital I–Q (in-phase and quadrature) detection derives the amplitude of A/B/C/D button signals. Beam position is then calculated from \(-/\sum\) of the four channels signals. Instead of traditional I–Q detection where and an NCO (numeric controlled oscillator) is used, NSLS-II BPM adapts the algorithm of the DFT (discrete Fourier transform) method [9]. A digital BPF (±2 MHz) is inserted to further decrease the bandwidth. TBT data is calculated from 310 samples block average of I–Q signal. FA and SA data are further processed from the TBT data.

A second signal-processing channel was added to measure two gate signals (blocks with blue lines in Fig. 2). Gate delay and width are controlled separately for two channels so that different beam induced signal within a turn can be processed. ADC waveform data can be selected after the gate1, gate2 or without gate (BPF in) to check the proper timing alignment of the gates.

![Fig. 2. Block diagram of two gate signal processing. Blocks with blue outlines are recently implemented for the gated processing.](image-url)
It is worthwhile to point out that Fig. 2 illustrates a typical digital IQ detection. The NSLS-II BPM selects the intermediate frequency at an exactly 80th harmonic of revolution frequency [9]. The cos/sin term can then be realized with a look-up table (LUT) and 310 samples after mixer are averaged to derive the TBT data directly. This 310 block average can be considered as a special low pass filter (LPF) and decimation, which typically doesn’t have a good blockage at high frequency. We are comparing the algorithm of the block average and specifically designed LPF. Performance of the two different implementations will be reported separately.

In order to acquire proper position data of beam signals from different bunches, it is important to align the timing of the two or multiple gates processing and adjust their width. With two bunch trains filled in the storage ring as displayed in Fig. 1, Fig. 3 gives the ADC aligned data for two gates. Gate1 aligns all the BPMs to process the bunch train #1 (150 consecutive bunches) signal, while gate2 processes the second bunch train (10 bunches with ~20 ns bunch to bunch separation) signal. Gate delay and width need to be adjusted according to the arrival time and length of the bunch train. The left two plots in the figure are ADC waveform data after gates of a particular BPM. Two turns ADC waveform data after the gates are shown. Gate1 width was set to 58 and gate2 width to 70 ADC samples. ADC data outside of the gate was set to 0 so that the TBT data was still processed from the 310 ADC samples. The right two plots show that 180 storage ring BPMs were aligned well for both gates. The colored areas in the mesh plots are the gated beam signals.

**Fig. 3.** Timing alignment of two gates. The left two plots show one BPM gated signal with gate1/2 select signals from individual bunch trains. The right plots are the gated signals for all 180 storage ring BPMs aligned to the same turn. BPM to BPM are perfectly aligned.
Two gated signal processing channels have been implemented on all NSLS-II storage ring BPM electronics. This allows the gated process of the beam-induced signal which improves the measures position resolution, especially for beam physics studies. The two gate functions enable other physics studies as discussed further in the next section.

Measurements

The position resolution for short bunch-trains can be improved by selecting properly gated ADC signals to be processed [7]. It has been presented in [1,2] that for a single bunch or short bunch train fill, BPM TBT data resolution can be improved by a factor of 3. The resolution depends on the signal-to-noise ratio, where beam induced signals only occupy a fraction of the turn for short bunch train fills (see Fig. 1 embedded plot); the noise, however, is proportional to the number of ADC samples to be processed (gate width). For long bunch train fills, as the beam induced signal occupies the majority of the turn, position resolution cannot be improved significantly since the gate needs to include all bunch signals.

We present several measurements at NSLS-II storage ring, using the BPM gate functionality: a) measure storage ring lattice with little disturbance to the stored beam; b) fast glitch motion detection; c) simultaneous measure the closed orbit of two bunch trains with high/low charge per bunch and d) other applications like the injection transient along the bunch train; wakefield measurement of two bunches etc.

Transparent lattice measurement

We have demonstrated that the NSLS-II operation lattice could be transparently characterized and corrected from the gated TBT data. A special filling pattern with a diagnostic bunch-train of ~1% of total charge filled, together with BxB transient excitations [1,2], are developed to fulfill the high precision linear lattice measurement, including betatron tune, beta-function, and phase advance. Fig. 4 gives the

![Figure 4](image-url)

**Fig. 4.** Beta-function measured with BPM gate and diagnostic bunches. Horizontal/vertical beta-beat was ~3.9/3.4% respectively.
beta-function measured from the diagnostic bunches at high current. With the BPM gated TBT data, the storage ring lattice can be characterized and optimized during normal operation.

**Fast glitch detection**

During the NSLS-II routine operation, 80% of buckets are filled. In this case, the gate function is helpful to measure fast instability, which causes coherent motion along the train. We have utilized the gate function to measure part of the bunch train positions, to detect the ion-induced instability due to vacuum activity in the storage ring. Bunches along the train will oscillate differently due to electron-ion interaction, as illustrated in the left picture of Fig. 5. About 1000 bunches, with 2 ns bunch separation, are filled in the ring. The empty gap of ~320 buckets allows the ion to escape. With the gap, fast ions [10–12] accumulated along the 1000-bunch train may cause bunch centroid oscillation or beam size increase. Typical ion-induced instability at NSLS-II appears at several MHz range [13], this is within the bandwidth of BPM analog BPF. The red curves in the illustration show the coherent bunch centroid oscillation due to fast ion accumulation. To detect such kind of motion, a BPM gate functionality is required, otherwise, the BPM measured TBT data will be averaged over all the bunches and not able to detect the unstable motions. As the fast ion induced oscillation increases and tends to saturate along the bunch train, the gate timing was adjusted to see tail bunches motion in the long bunch train fill (shown as blue window and arrow).

A fast glitch detection function has been recently implemented, by checking the BPM TBT positions. If the TBT position goes beyond a pre-defined threshold window, BPM waveform data can be captured. The right side of Fig. 5 gives a snapshot of fast transient motion captured during the 350 mA top-off operation. As can be seen, vertical TBT position moved by more than 20 μm, which was the defined threshold. The horizontal position had ~10 μm level oscillation. BxB data from the feedback system has been captured while the glitch happens, and the frequency domain unstable mode analysis reveals a clear ion-related instability. A detailed discussion of the glitch detection and analysis will not be covered in this paper.

**Gated close orbit measurements**

Closed-orbit difference between low and high charge fills has been used to characterize the local impedances [14,15]. Without the gate functionality, the beam orbit difference was measured at

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**Fig. 5.** Ion induced instability observed with gate functionality during the top-off operation. Left: Illustration of fast instability along the bunch train and BPM gate to detect the motion; Right: TBT position in the horizontal/vertical plane. The glitch was detected at turn #0. Vertical position spiked by more than 30 μm peak was noticed in vertical plane.
different times when the machine was filled with low/high charges. The machine jittering/drifting affect the close orbit measured at different times. In case the impedance-caused orbit change is comparable to the machine jittering/drifting, the method of measuring the orbit at different times fails because it is impossible to distinguish whether the difference is due to impedance or jitters.

With two gates, beam orbits for two separated bunch-trains can be measured synchronously. As the positions are measured at the exact same time, the machine jittering/drifting can be neglected. Besides, one of the gate position readings can be used as a reference and measure the other gate position changes. This is of particular interest to study the machine impedance globally or locally.

Fig. 6 gives an example of the closed orbit difference measured by two bunch trains with low/high charge fills respectively. The gate1 measures the orbit of low charge per bunch (6 μA, to have sufficient BPM resolution, a multi-bunch train of ~150 bunches was filled), while gate2 measures the orbit of high charge per bunch (~0.3 mA, 10 single bunches were filled in the gate to have comparable signal strength as gate1). The vertical scraper blade was moved to different positions (−10 mm, −7.5 mm, −5 mm, −3 mm) to vary the local impedance. Only the lower blade was used for the study. The closed orbit difference compared to the scraper fully out position (−12.5 mm) is plotted. Taking advantage of two gates position data available, fast orbit feedback was turned on to maintain the low charge bunches orbit. This minimizes the machine orbit jittering so that small close orbit difference between the two gates can be measured precisely.

Comparing the orbit difference of low/high charge bunches, one can estimate the local kick strength by applying orbit response matrix. Using the response matrix between correctors and BPMs, the closed orbit difference at scraper position of −3 mm estimates the corrector strength of ~1.3 μA near the first two correctors. The vertical scraper is located on the same girder. Local kick effect by the intrude scraper blade can be identified. Transverse local impedance can be inferred from the measured orbit difference.

We continue discussing the measurement of the local impedance of an in-vacuum undulator (IVU) with two gated orbits. Fig. 7 shows the result with angular local bumps at one of the IVU installed in the storage ring. A vertical angular bump ~0.7 m rad was created at the IVU, as seen in the top picture. The IVU was shown as the blue rectangle. The horizontal scale was adjusted so that the 0 is the IVU.

![Image](image.png)

**Fig. 6.** (top) closed orbit difference of two gates at various vertical scraper blade positions. (bottom) localized the kick source from orbit different by applying inverse orbit response matrix.
The orbit difference of two gates along the ring is plotted in the bottom. This orbit difference is purely due to bunch charge difference between the two gates. The IVU location is marked with a red arrow. Similar to the vertical scraper case, the virtual kick location can be determined by response matrix of the storage ring to be near the IVU location. We have measured the closed orbit of the two bunch trains with parallel local bumps and different IVU gaps.

Similar measurements can be applied to other insertion devices or vacuum components, to symmetrically study the local impedance in the storage ring. Transverse kick factor can be further analyzed quantitatively from these measurements.

Other applications

Due to injection kickers mismatch, the stored beam is disturbed during top-off injection. This kind of injection disturbance can be systematically measured along the bunch train with gate and w/o gate (1000 bunch filled). By changing the gate delay, the injection kick mismatch caused bunch motions can be precisely measured piece wisely. The piecewise orbit information could be used to optimize/match four kicker magnets pulse profiles and delays to mitigate the disturbance due to the injection transient. On the other hand, TBT data without gate only measures the averaged orbit distortion for all bunches.

There are other physics measurements, which can be carried out using the gated functionality. For example, one may directly measure the transverse wakefield with two bunches. The preceding bunch can be displaced by resonant excitation, while the trailing bunch affected by the Wakefield of the preceding bunch (es) can be characterized. By filling two bunches at difference separation, this method can be used to probe the medium range wakefield lasts within one turn period. The kick amplitude of trailing bunches can be measured at: 1) various distance from the preceding bunch; 2) various the preceding bunch oscillation amplitude; 3) various the preceding bunch current; 4) various the driving frequency etc. Similar measurement has been reported in single pass machine [16], it will be an interesting topic if the measurement is successful in the storage ring.
Discussion and future developments

With the gate functionality implemented at the NSLS-II BPM electronics, we have measured the storage ring lattice using a small fraction of bunches filled in the ring. Collective effects with low/high charge fills have been studied with simultaneous data acquisition of two gates. Charge-dependent orbit difference caused by insertion devices and scrapers has been studied. Besides, other physics measurements can be carried out using this functionality.

The existing gated BPM can only measure two bunch clusters (trains) thus far. Due to the limitation of the analog bandwidth and digitizer sampling rate, it's not possible to measure bunch to bunch positions separated by 2 ns. From the transverse feedback system, the BxB position can be measured at a particular location. Bunch-to-bunch tune, coupled bunch instability modes, and other BxB behaviors can be measured even with the one such kind of system in the ring. However, lattice characterization and collective effect studies will benefit if all the BPMs can measure the BxB positions. It is desirable to have BxB position measurement capability for all the BPMs (or at least a good portion of them). With large bandwidth (>250 MHz to detect 2 ns bunch separation), the analog signal conditioning, timing jitter, and measurement resolution are of concerns and need to be handled properly.

A prototype BxB position BPM electronics has been tested at NSLS-II, with promising results. A 500 MHz 14-bit ADC evaluation board was used to digitize the button signal with 2 ns separation. About 5 µm BxB position resolution was achieved with ~0.35 mA per bunch current (325 mA/1000 bunches). TBT position resolution averaged from 1000 bunches was ~0.5 um. We will report the future progress as the development of BxB BPM is moving forward.

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