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BEAM MEASUREMENT DURING SWAP-OUT INJECTION OF THE APS-U STORAGE RING*

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Abstract

The Advanced Photon Source Upgrade (APS-U) implements a novel swap-out injection scheme. To comprehensively characterize the beam dynamics during swap-out injections, approximately 20 beam position monitors (BPMs) in the initial sections of the storage ring have been equipped with high-precision single-bunch electronics. These systems measure the turn-by-turn (TBT) positions of the injecting bunch. Using similar techniques, the longitudinal phase and energy of the injecting bunch can also be accurately assessed. This paper presents results of beam measurements during swap-out injections using these advanced systems.

INTRODUCTION

APS-U is an ultimate low emittance storage ring [1] that has been constructed and commissioned at Argonne National Laboratory. To accommodate the small dynamic aperture of the storage ring, swap-out injection [2] scheme is used.

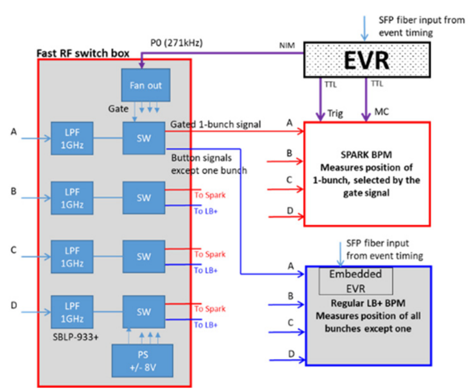

Figure 1: Schematic of the single-bunch BPM.

A single-bunch BPM system, with fast RF switches and high precision electronics, has been designed, implemented, and commissioned. The fast RF switches are capable of selecting any bucket in the storage ring, with a focus on the swap-out injection target bucket. The principle of the system and earlier test results on the original APS machine were introduced in [3]. As shown in Fig. 1, the button BPM signals pass through the fast RF switches. A 1-bunch signal is gated to the Libera Spark electronics, while the signals from the remaining bunches are routed to regular electronics of Libera Brilliance+ (LB+). The Micro Research Finland (MRF) timing system provides the related clocks for the RF switches and electronics. The system can measure a selected bunch (e.g., the swap-out bunch) during machine studies and operation. Precise single-bunch TBT measurement of the x/y positions and the sum signals help characterize the injection.

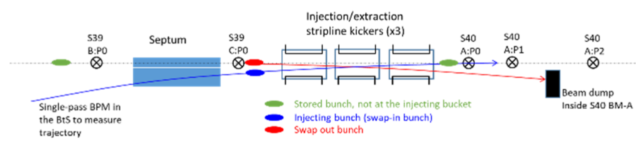

Figure 2: Swap-out injection scheme and nearby BPMs equipped with single-bunch BPM electronics.

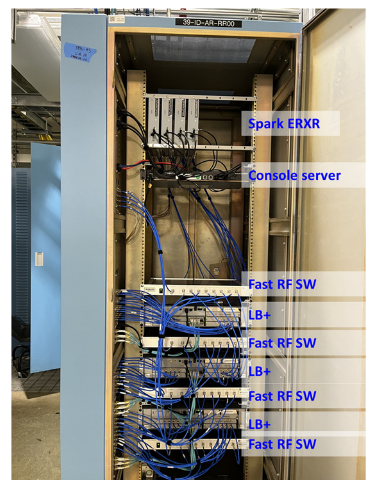

Figure 3: Installed BPM electronics in one section of the ring with RF switches and Libera Sparks.

A total of 18 BPMs from the first three sectors are equipped with single-bunch, single-pass electronics [4, 5] to measure the trajectory of the newly injected bunch and the betatron motions of the swap-out bunches (for both the old bunch to be kicked out and the new bunch being injected). Additionally, two BPMs near the injection area (S39CP0 and S40AP0) have single-bunch electronics for various diagnostics. See Fig. 2 the BPMs near the injection straight and Fig. 3 for the installed electronics in one of the mezzanine racks. The rack shown has four BPMs equipped with single-bunch electronics.

We report commissioning and beam measurements in the APS-U storage ring, most of which are related to swap-out injection.

TIMING ALIGNMENT

The P0 clock at 271 kHz is used to select a single bunch for the Spark electronics; its width and precise delay are controlled in the MRF EVR modules. Similarly, the EVR provides P0 fiducial and trigger signals to the Spark electronics. Figure 4 shows a typical ADC waveform of the gated single bunch. There are 398 ADC samples per turn for APS-U BPM electronics, and for the 1-bunch signal, it

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typically spans 300 ns (~30 ADC samples with 9 ns per sample) due to the band pass filters. Depending on which bucket is gated, the waveform may appear at different locations within a turn. The Spark phase offset can then be adjusted to place the 1-bunch waveform within the processing window of a turn. During swap-out injection, as the target bucket keeps changing, the 1-bunch signal may move to the edges between turns and leak into the next turn. The automatic targeting of the swap-out bunch is further reported in [6].

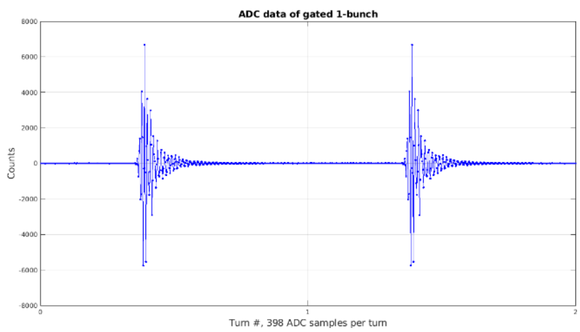

Figure 4: ADC waveform data of one selected bunch as detected by a Spark unit. Two-turn signals are plotted for one button; 398 ADC samples per turn.

While most of the measurements for the single-bunch BPM are for the swap-out injecting bucket, the system is flexible and allows selection of any bunch. This allows the detection of, for example, injection disturbances to trailing bunches, filling pattern measurements, and disturbances to individual bunches from the pinger or other pulsed kickers, etc. As tested in the old APS ring [3] and in the upgraded APS-U ring, the system is capable of achieving TBT resolution of approximately 1 µm at high single bunch current.

INJECTION TRANSIENT

Figure 5 shows a typical TBT sum and x/y position transient during a swap-out injection. At ~200 turns before injection, the swap-out bunch gets a decoherence kick (DK) vertically so that it will not damage the beam dump (collimator). The new bunch is injected at turn 0 in the horizontal plane. For BPMs between the septum and the beam dump (S39CP0, S40AP0, and S40AP1, see Fig. 2), two bunches are present during the swap-out turn when the injection kickers (IKs) fire, which is why the sum signal and x position spike at the injection turn. Other single-bunch BPMs see only one bunch at the injection turn. For the plotted example, the sum signal increased ~17.5 %, meaning the newly injected bunch had ~17.5 % more charge than the old swap-out bunch. The TBT sum signal provides additional information on the injection efficiency and possible charge losses when combined with other charge/current monitors.

The stripline-based injection kickers and high-voltage pulsers have pulse width of ~10 ns, which kick the injection/extraction bunches. However, due to reflections from not perfectly 50-Ohm matched parts (mostly from the stripline kicker feedthroughs), a small fraction (5-10 %) of the 27 kV pulse is reflected and can disturb the trailing

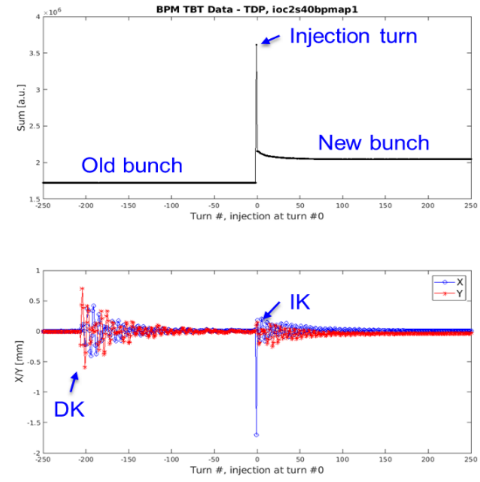

Figure 5: A typical injection transient of the swap-out bunch. The spikes at injection turn are due to the presence of both the incoming and outgoing bunches.

bunches. Using the single-bunch system, TBT disturbances of trailing bunches following the injecting bucket can be measured. It has been observed during 216-bunch operation that the bunch about ~60 buckets following the main injecting bunch experiences strong disturbance. The disturbance is then fully characterized during a study where a single bunch is stored and then the IKs are fired at different bucket offsets relative to the stored bunch. See Fig. 6, the Xrms/Yrms were calculated from 40 turns of motion following an injection kick. A large disturbance is seen at 62 RF buckets away, which corresponds to ~176 ns. This agrees with the reflection as measured on the IK waveforms. The disturbance at 118 RF buckets is likely due to a second reflection. It is worth noting that Fig. 6 shows the combined disturbance from all three IK kickers. Disturbance from individual kickers can be measured by the same method.

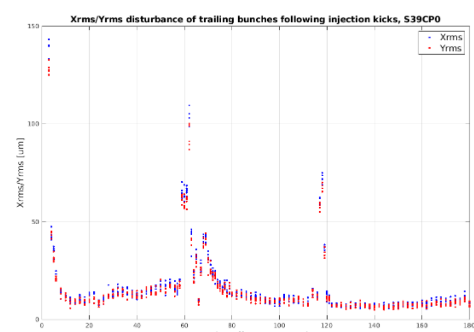

Figure 6: IK disturbance to the trailing bunches.

Like the IK disturbance, the turn-to-turn disturbance of individual bunches can also be measured following other pulsed kickers like DK and the pinger. Although DK uses the same stripline feedthrough which is believed to con the same stripline feedthrough which is believed to contribute to the reflection, the DK does not contribute much to trailing bunches as the kick voltage is smaller (10 kV vs. 27 kV) and it uses a shorter stripline kicker (smaller deflection angle, 0.15 mrad for DK; as a comparison, each IK delivers 1 mrad kicks and 3 mrad for three).

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RELATIVE PHASE MEASUREMENT

The BPM electronics can process the button signal in I/Q mode as one of the signal processing methods. While typically the amplitude is used for position measurement, the phase from the I/Q detection can be used to measure the relative beam phases. It has been noticed that the direct phase signal drifts, but the relative phase between different channels can be accurate if a button signal and an RF reference signal are compared. The setup is similar to [7], in our case, we have a 1-bunch gated signal sent to channel A, and another button signal sent to channel B. Channels C and D have carry RF reference signals. This way, the relative phase between A and D measures the beam phase of a single bunch. The relative phase between B and D measures the beam phase of all the bunches. And C/D characterizes the measurement resolution.

Relative 1-bunch phase turns out to be a useful tool for longitudinal dynamics measurements. Combined with the ΔE/E measured at a dispersive BPM, the longitudinal phase space of individual bunches can be measured. Figure 7 gives an example of such measurement at injection. Injection beam phase and energy can then be optimized based on these measurements.

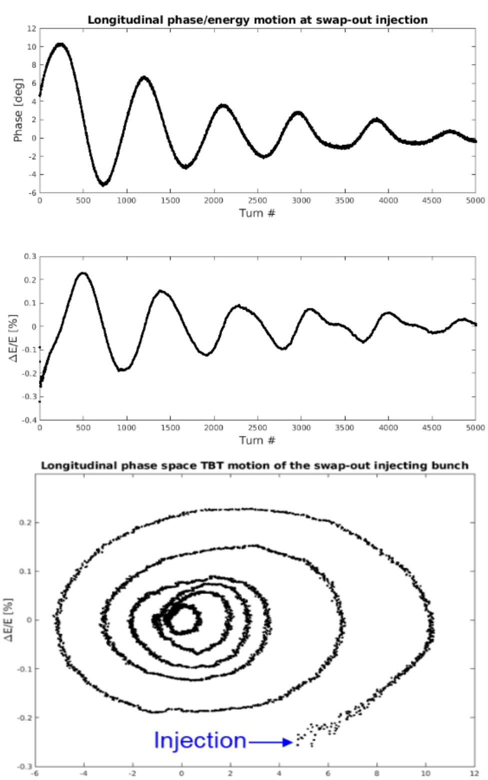

Figure 7: Longitudinal phase and ΔE/E measurement for the injecting bunch (top) and its phase space motion (bottom).

Relative phase shift at different single bunch currents has also been measured, which may be used to analyze the real part of the longitudinal broadband impedance. The TBT phase data can also be used for other longitudinal diagnostics, for example to precisely measure the synchrotron frequency. We plan to report these results separately.

BPM SUM AND BUNCH CURRENT

BPM button signal or the sum of four buttons is linear with single bunch current, hence it can be used to measure the turn-to-turn bunch current of the injecting bucket. We have one BPM (S40AP0) configured with a combiner/splitter so that it can be used to characterize the TBT resolution. The sum signal measured from this BPM is not affected by position changes and thus better serves as a current monitor.

Among the two signal processing methods [8], TDP (Time Domain Processing) and DDC (Digital Down-Conversion), the 1-bunch measured sum (or button amplitude) is linear to the single bunch current. It is worth pointing out that TDP button amplitude or sum can be nonlinear for other bunches as the fill pattern varies. This can be explained in the frequency domain as beam spectrum around the RF frequency changes and TDP processes a wider spectrum (±10 MHz). On the other hand, the DDC channel only processes the signal at the RF frequency.

SUMMARY AND DISCUSSION

A single-bunch TBT measurement system has been installed and commissioned for the APS-U storage ring, allowing precise TBT measurements of a selected bunch. This system has been used for injecting beam trajectory measurements and other injection transient measurements during swap-out operation. The single bunch sum signal provides valuable information about bunch current. A small reflection of the button signal has been observed as the button BPM side is not matched to 50 Ohm.

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