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PRECISE SINGLE BUNCH MEASUREMENTS USING FAST RF SWITCHES*

W. Cheng#, A. Brill, Argonne National Laboratory, Lemont, IL 60439, USA

Abstract

To measure the swap-out injection/extraction bunches of the Advanced Photon Source Upgrade (APS-U) storage ring, single-pass Beam Position Monitor (BPM) electronics will be installed in the first sectors after the injection with fast RF switches. The fast RF switch will select a bunch signal to be processed by the single pass BPM electronics, and have the remaining bunches processed by the regular BPM electronics. In addition to measuring the swap-out bunch during injection, the setup will be able to carry out various other measurements of any selected single bunch (or bunches). This paper presents the performance of the fast RF switches and related electronics.

INTRODUCTION

APS-U is an ultimate low emittance storage ring [1] that is being constructed at Argonne National Laboratory. The machine has small dynamic aperture, hence swap-out injection will be used. It is of great interest to measure one selected bunch (like the swap-out bunch) during machine studies and operation. Precise 1-bunch measurement of the X/Y positions (and sum signals) in turn-by-turn (TBT) rate will supply important information to machine physicists. For example, it will make sure the swap-out bunch get pre-kicked; it allows single-turn trajectory measurement during the injection/extraction period; and it will be able to confirm that a fresh bunch is captured with a desired intensity.

Modern BPM electronics typically use 125 MHz, 16-bit ADC digitizers. There are band-pass filters (BPF) implemented in the analog front end to select button BPM signal around the RF frequency (or at its harmonics). For example, APS-U storage ring will be equipped with such BPM electronics [1], with +/-10 MHz BPF and ADC sampling at 108 MHz (revolution frequency × 398). Due to the BPF, the single bunch signal will be stretched to ~300 ns, making single-bunch position measurement impossible if the bunch-to-bunch spacing is less than that. For the APS-U machine, the bunch spacing will be either 11.4 ns (324-bunch mode) or 76.7 ns (48-bunch mode), both are small enough so that regular BPM electronics will not be able to measure individual bunches.

Wider band digitizers allow bunch-by-bunch (BxB) measurements. These new digitizers have been tested at various machines [2-4]. However, due to its wider bandwidth, there are limitations of the BxB position measurements:

- The BxB resolution is worse due to the wider bandwidth, and the ADC digitizer will have less resolution (8 to 12-bit for a broadband ADC vs. 16-bit for a regular BPM electronics).
- The number of turns that can be saved is limited.
- It is more difficult to process and stream out the data.
- The measurement may be sensitive to clock jitter, bunch lengths and synchronous phases, and depends on the algorithm to process the BxB positions.

As in many cases, it is good enough to measure one selected bunch at the TBT rate. Fast RF switches have been proposed to select the 1-bunch signals before sending them to regular BPM processing electronics. It has been demonstrated that the regular BPM electronics have very good single bunch TBT position resolution. The single-bunch BPM electronics setup is illustrated in Fig. 1. At each selected BPM pickup location, the four button signals (namely A/B/C/D) pass through a fast RF switch box. The fast RF switch will choose a single-bunch signal for the single pass BPM electronics, and the remaining bunch signals continue feed to the regular BPM electronics (Libera Brilliance+ or LB+). The fast RF switch unit (gray box on the left which includes four switch boxes; and a dedicated Spark BPM electronics (gray box on the bottom right) select and measure the one-bunch TBT positions/sum. The blue line box shows the regular LB+ electronics which measures the position of all bunches except one.

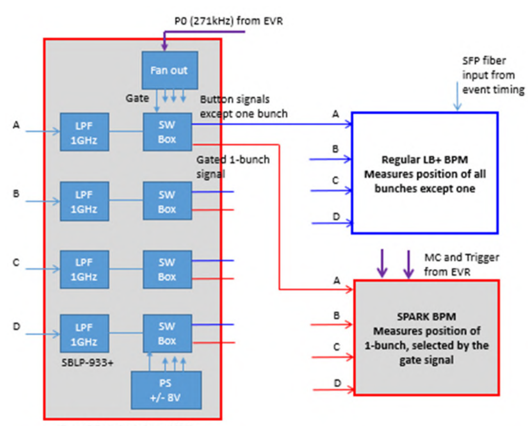

Figure 1: Schematic setup of the single pass BPM.

There will be about 20 BPMs (selected in the first three sectors right after injection) in the APS-U storage ring to be equipped with the single bunch TBT BPM electronics. Using these BPMs, the injected bunch phase space can be measured [5, 6]. Additionally, TBT position and sum signals from these BPMs will be useful to track the swap-out bucket for the pre-kick, extraction, and injection process. The idea of fast RF switches to select 1-bunch signal has been implemented in KEK's ATF and SuperKEKB [7, 8]. We report the procurement status and

*Work supported by DOE contract No: DE-AC02-06CH11357
wcheng@anl.gov

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beam test results of the RF switches, the single-pass BPM electronics (Libera Spark) and regular LB+ BPM electronics.

PRODUCTION STATUS

There are 560 LB+ BPM electronics ordered. All of these regular BPMs have been received, see details of the production status and performance at [9].

The fast RF switches and single pass BPM electronics (Libera Spark) had contract awards in April 2021. First article units have been received and tested in June/July. Production units are expected to be delivered in October 2021.

The fast RF switch first article units have been tested on the bench to characterize the input/output port VSWR, insertion loss, isolation, and switching noise. Figure 2 gives example of the measured insertion losses from the input port to the two outputs (input -> out1 which will be connected to LB+ with RF switch in "off" state; input -> out2 which will be connected to Spark with RF switch in "on" state). It's worth mentioning that there are Mini-circuits SBLP-933+ [10] low pass filters (LPF) added in front of the switch input port. The LPF is used to filter out the high frequency beam signals, and it may contribute part to the insertion losses especially for high frequencies. VSWR of the input port is affected by the LPF as well.

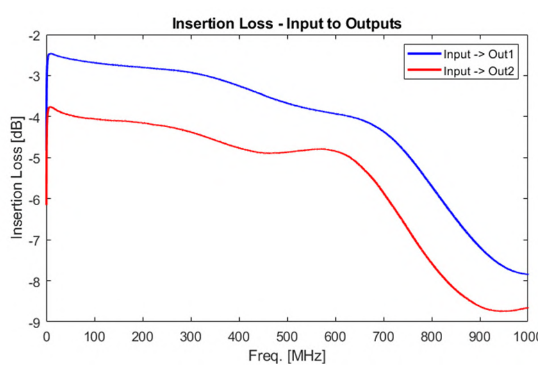

Figure 2: Typical measured insertion losses of the RF switches. At 352 MHz where the BPM electronics operate, the insertion losses are 3.07 dB and 4.58 dB, respectively.

A typical time domain response of the RF switches is shown in Fig. 3, where Ch1 is the gate signal with 10 ns width; the input 352 MHz signal was switched to out2 (Ch3) when the gate is on (-0.8 V) and out1 (Ch2) when the gate is off (0 V). The RF switches work well down to a width of 4-6 ns, which is well below the minimum bunch spacing of 11.4 ns. The RF switching noise was measured to be several mV with no input signal. The switching noise is much smaller than the typical beam induced signals.

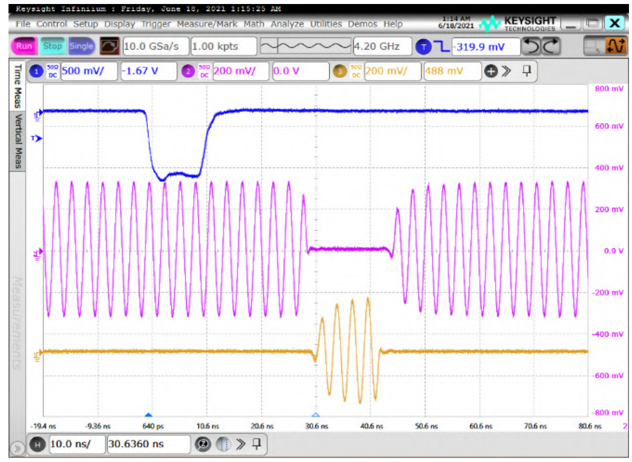

Figure 3: Typical response of the RF switches in time domain. 352 MHz CW signal was connected to the input port at 1 Vpp (+4 dBm). Ch1 (blue) – gate signal applied to the switches, 10 ns width; Ch2 (magenta) – out1 of the switch, this is the output signal outside of the gate; Ch3 (orange) – out2 of the switch, this is the output signal within the 10 ns gate.

Like the LB+, the received Spark electronics have been tested in the lab with good performance. Single bunch measurement resolution is more relevant for this application as the Spark electronics will normally measure 1-bunch signal. See the next section of beam measurement results at the APS storage ring.

APS BEAM TESTS

Beam Test Setup

The fast RF switch and Spark units, together with the LB+ electronics, have been installed in the APS machine for studies and parasitic monitoring during APS user operations. A dedicated BPM four-button signals were connected to the fast RF switches as shown in Fig. 1, the outputs of the switches fed to Spark and LB+ respectively. Timing signals have also been prepared to properly select the bunches. Figure 4 is a picture of the electronics installed at S27.

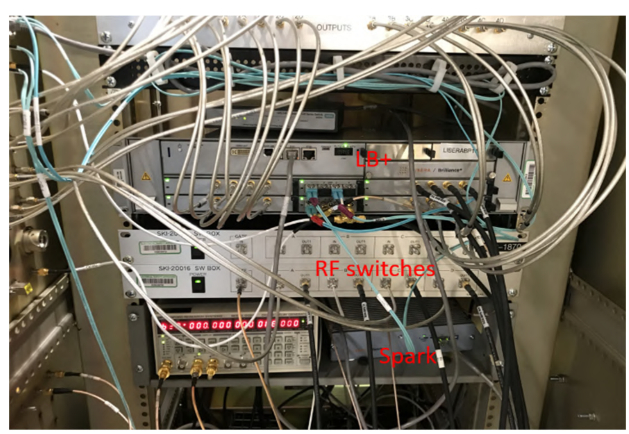

Figure 4: Beam test setup at S27 of the APS machine.

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Existing APS button BPM signals were used (S27A:P3) for the beam tests. As compared to the APS-U button, the APS BPM has larger button sizes and transverse chamber profile. The button signals have been compared to be similar. With the same bunch lengths, button capacitance and beam current, the signal at 352 MHz (RF frequency) differs by ~0.7 dB. This means the measured results from the existing A:P3 BPM signals will be valid for the future APS-U BPM.

During regular 24-bunch, 102 mA APS top-up user operation, one bunch signal can be selected by the RF switches. As shown in Fig. 5, one of the 24 bunches (Ch3, orange) was gated out to be sent to the Spark BPM. The other 23-bunch signals (Ch2, magenta) were connected to LB+. A 10 ns gate width was used (Ch1, blue), and the delay was adjusted to select any of the 24 bunches. There was a 20 dB attenuator pad added at the RF switch input.

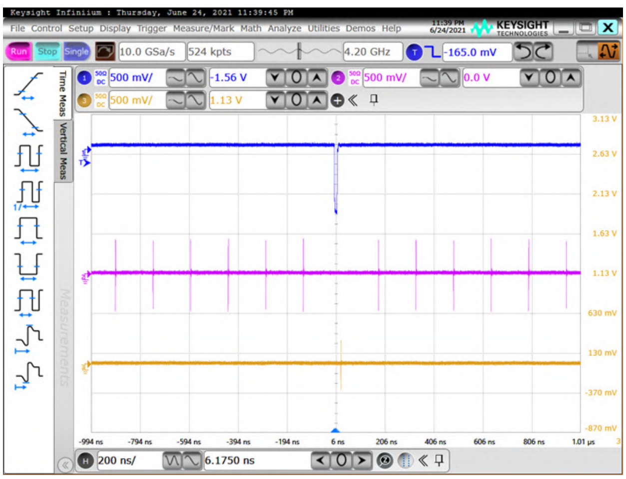

Figure 5: Button BPM signals of the fast RF switch output. The gate input (blue) is configured to select the signal from a single bunch (orange) to send to the single-bunch Spark BPM. The remaining 23 bunches (magenta) are measured by the standard LB+ BPM.

Single Bunch TBT Resolution

The Spark BPM TBT resolution has been measured at various single bunch currents. The results are plotted in Fig. 6. There were two Spark electronics connecting to S27A:P2 and S27A:P3 signals respectively. The Libera Spark electronics process the TBT data in DDC (Digital Down Convert) mode or TDP (Time Domain Process) mode, TDP mode gives better resolution for single bunch fill. With stored beam current above 1mA, the typical TBT resolution was measured to be around 1 um. The front-end attenuator was set to 0 dB for low currents (<1 mA) and adjusted for higher currents to avoid ADC saturation. It was not tested during the study, but the TBT resolution is expected to be further improved with proper mask.

Adding the RF switches will decrease the signal level 3-4 dB, as shown in Fig. 2. The single bunch TBT resolution was measured with the RF switches to be ~1 µm resolution with roughly 1 mA stored beam. The switching noise affects the TBT resolution at very low current (<0.2 mA), but the resolution is still well below the 30 µm specification.

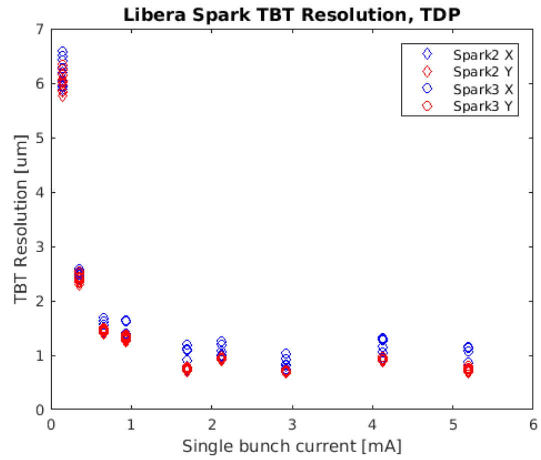

Figure 6: Libera Spark TBT resolution (in TDP mode), at various single bunch currents.

First-turn injected bunch resolution has been measured as well. With ~1 nC charge, the first turn position had RMS jitter of less than 10 µm.

Injection Transients

To further test the TBT dynamics measurements during injection, the RF switches and single bunch Spark electronics have been used to monitor APS top-up injections. One bunch signal was gated out by the RF switch and fed to the Spark, while the remaining 23-bunch signal was connected to the LB+. The gated 1-bunch was at bucket #432.

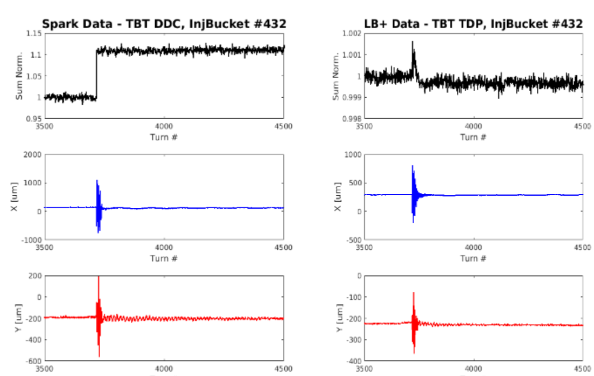

Figure 7: TBT data measured during APS 24-bunch top-up operation. Left side plots are for the gated 1-bunch measured with Spark electronics; right side plots are for the remaining 23 bunches measured by LB+.

Figure 7 shows the TBT sum and positions while the gated 1-bunch got a top-up injection. The bunch charge increased ~10% which is a clear indication that injected charge was captured. The sum signal measured on the remaining 23 bunches did not change, as expected. Both

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BPMs see injection transients in the x/y positions. The event trigger occurs ~2700 turns before the injection, and BPM electronics are capable of acquiring TBT waveform data prior or post trigger with user-defined turn offsets. In the particular example, the offsets were set to -1000 turns. That was the reason that the actual injection took place at turn #3700. When injection was made to any of the 23 bunches monitored by the LB+, the sum signal for the LB+ increased and the Spark electronics didn't see any charge accumulation.

What is measured here is similar to the APS-U swap-out injection. The difference is that the APS storage ring uses accumulation injection, and for the future APS-U, the bucket will be totally refreshed with a new injecting bunch. With proper timing adjustments, the RF switches and electronics will be able to monitor the swap-out injection beam dynamics.

Effect on the Regular BPM

While the RF switches select different bunches, the measured positions on the other bunches shall not be affected. This has been checked during the APS 324-bunch operation. By gating a single bunch and adjusting the gate delay to select different bunches, the LB+ (measuring 323 bunches) position variation was less than 0.5 μm peak-to-peak. This included the actual beam drifting during the bunch scan, so the electronics effect is less than that.

SUMMARY

A single bunch TBT measurement system has been proposed and tested for the APS-U storage ring. The system allows precise TBT measurement of a selected bunch and proves to be important for the beam dynamics measurement of the swap-out bunch. This method shall be useful for other machines with similar swap-out injection scheme, or for existing storage rings with accumulating injection. Using commercially available RF switches and BPM electronics, a single bunch TBT resolution of 1 μm can be achieved. Beam tests at the APS machine demonstrate that the system will work well for the APS-U, with either 48-bunch mode or 324-bunch mode.

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