USES OF TURN-BY-TURN DATA FROM FPGA-BASED BPMs DURING OPERATION AT THE APS STORAGE RING *

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Abstract

The Advanced Photon Source (APS) has started a program of upgrading old beam position monitor (BPM) electronics to new FPGA-based devices. We present here the use of such BPMs for online measurement of betatron tunes during top-up operation. In top-up injection, the stored beam is kicked and experiences betatron oscillations that can be used for online monitoring of the betatron tunes. Also, due to kicker waveform time dependence, different bunches experience kicks of different amplitudes. By collecting data from different bunches, we can also monitor tune shift with amplitude. In the case of APS, the matter is complicated by the very fast decoherence of oscillations. We describe methods used to derive tunes and present results of online monitoring.

INTRODUCTION

The Advanced Photon Source (APS) broadband monopulse beam position monitor (BPM) system is designed to measure single- and multi-turn beam positions used in a feedback system to control both AC and DC orbit motion. Presently, a VXI-based signal conditioning and digitizing unit (SCDU) is used for data acquisition. Compared to today's technology, the SCDU is outdated, and needs a technology upgrade. The upgrade, now underway, reuses the monopulse receiver from the existing SCDU and replaces the SCDU with an FPGA-based VXI data acquisition and processing module [1]. The new BPM signal processor (BSP100) contains eight ADCs sampling at a 88 MS/sec rate, an embedded IOC, and a single Altera Stratix II FPGA. It can acquire and process data for four monopulse receiver units. Old BPM electronics are being gradually replaced at a rate of about two sectors every shutdown. Presently, five sectors out of 40 are equipped with the new electronics.

MEASUREMENTS

The APS storage ring operates in top-up mode about 75% of the time. Depending on the fill pattern, top-up injection is performed at intervals of one or two minutes. At every injection, one bunch is injected into the the bucket with the lowest charge. The APS operates with the mismatched bump injection, and therefore the stored beam experiences betatron oscillations at every injection. The beam motion is recorded and analyzed for every injection; this is primarily used to monitor betatron tunes. Figure 1 shows an example of the horizontal betatron motion.

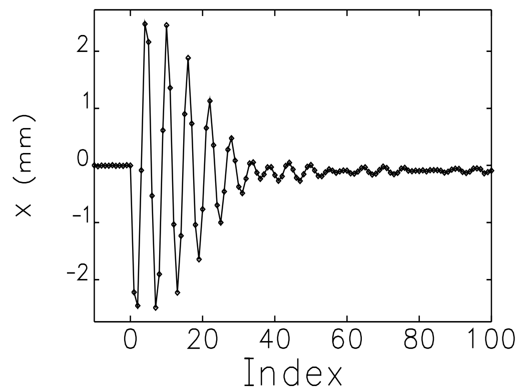

Figure 1: Horizontal betatron motion after injection.

Two BPMs are dedicated for betatron tune monitoring: S38A:P2 is used for horizontal motion and S38A:P4 for vertical motion. We use two devices because the BPMs can provide information on only one plane every turn or both planes on every other turn. Presently these two BPMs are configured in such a way that they always record the oscillations of the same bunch – bunch number 0. During top-up, the injection is performed into different buckets, whatever bucket has the lowest charge. The kicker magnet waveform has a length of about 3 μs, which covers approximately one turn. This means that at every injection bunch 0 experiences oscillations with a different amplitude, depending on which bucket received the injection.

From Fig. 1 we can see that the motion completely decoheres in about 30 turns. This is the result of operating with high chromaticity, high nonlinearity, and high bunch charge (more comments on this matter later). In order to determine tunes and oscillation amplitude from such a short set of data, we perform a fit of the oscillations. However, since the parameters affecting the decoherence rate constantly change, we decided to fit the data using several functions and then choose the best result. Among the changing parameters are the amplitude of the motion, which changes from shot to shot depending on what bucket receives the injection, and chromaticity and nonlinearities that change between different fill patterns and lattices. The functions that we use are the equation of decoherence due to tune shift with amplitude and chromaticity [2], and several combinations of various exponential decays.

Figure 2 shows the oscillation amplitude of bunch 0 as a function of the injected bucket number. The data were obtained for the fill pattern of 24 equally spaced bunches

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(the most common fill pattern at the APS). Points show the data accumulated in a 24 -hour period of time, and the lines connect the average values. We can see that the amplitude of the horizontal motion after injection varies from 1 to 3 mm, and in the vertical plane it changes from 0 to 0.5 mm. We note here that there should be no kick in the vertical plane unless we have tilted kickers and/or skew quadrupoles inside the kicker bump. There was actually one skew quadrupole magnet inside the bump that was powered as a part of the coupling control. After we started recording these turn-by-turn data, we found that if we turned off this skew quadrupole, the amplitude of the vertical oscillation of the beam would decrease. The data presented in Fig. 2 already show the case with the skew quadrupole turned off.

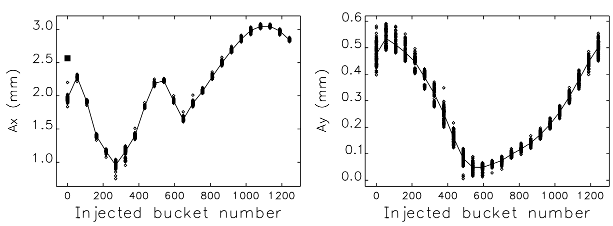

Figure 2: Horizontal (left) and vertical (right) amplitudes of bunch 0 motion as a function of the injected bucket number.

One interesting feature of the plot is the point at bucket 0. The dependence of the amplitude on the bucket number is quite smooth, and it is natural to expect that the point at bucket 0 should be an average of points at the nearest filled buckets 54 and 1242. That point is represented on the plot as a standalone black square. The difference between that point and the measurement is about 25%. To understand this difference, we need to remember that for bucket 0 we measure the motion of the bucket that is actually receiving the injection. That means that there are two bunches present in bucket 0, i.e., stored bunch and injected bunch, and those bunches oscillate in approximately opposite phases. But since the stored bunch has more charge, we see this only as a small reduction of the amplitude. During the observation period presented in the plot, there was one injection into bucket 0 when most of the injected beam was lost in the booster and the total injected charge was very low. Actually, it is this point that is shown as a larger black square on the plot.

Having different amplitudes of the motion allows us to measure tune shift with amplitude due to sextupole nonlinearities. Figure 3 shows tune shift with amplitude for horizontal (left plot) and vertical (right plot) planes. The same data are used as in Fig. 2, and bucket 0 is excluded due to its lower that real amplitude. One can definitely see the parabolic dependence of the horizonal tune on the left plot.

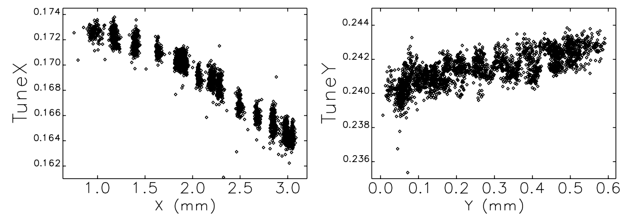

Figure 3: Betatron tune dependence on the oscillation amplitude. Left plot - horizontal tune vs horizontal amplitude; right plot - vertical tune vs vertical amplitude.

Long Term Tune Monitoring

As mentioned earlier, we do not presently monitor betatron tunes online at the APS. The new BPMs give us this possibility without any additional beam disturbance by just analyzing the beam motion after every top-up injection. Figure 4 shows betatron tunes over one week of storage ring operation. To exclude the tune variation due to tune shift with amplitude, only injection into bucket 0 is shown. One can see a tune variation of the order of 0.001.

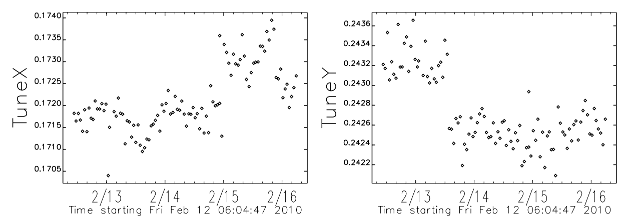

Figure 4: Horizontal (left) and vertical (right) betatron tune variations over the course of five days. Only injection into bucket 0 is shown.

The actual waveform acquired by BPMs is very long – about 240,000 turns – and only a very small portion of it contains betatron motion. We use the entire waveform to determine the synchrotron tune using FFT. The tune and amplitude of the synchrotron motion is found by integrating the FFT spectrum. Figure 5 shows amplitude and tune of the synchrotron motion for the same period of time as in Fig. 4. One can see that bunch 0 exhibits higher oscillation amplitude and tune (the points at the top part of the plots) when injection is performed into this bucket. The higher oscillation amplitude can be explaned by energy error of the incoming bunch (this can actually be seen on the waveform). The injected particles also oscillate at higher tune, which does not have a simple explanation.

COMPARISON WITH THE MODEL

We compared the measured motion to simulations using real kicker settings, a calibrated model, and real sextupoles. For the kickers we used calibration of 0.105 mrad/kV, which was measured some time ago for small kicker amplitudes. The rf voltage in simulations was chosen to get the measured synchrotron tune. We didn't use wakefield

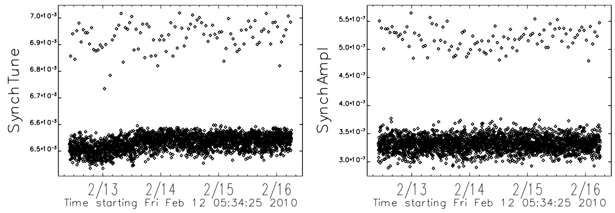

Figure 5: Synchrotron tune (left) and amplitude (right). The points at the top of the plots correspond to injections into bucket 0.

effects in simulations. Figure 6 (top row) shows the comparison of the horizontal motion. The initial amplitude of the kick for the measurements and the simulation matches pretty well (no fitting was done here). However, decoherence time is significantly different. Also, the measured motion does not show any recoherence that can be seen in the simulations (right plot, top row).

The bottom row of Fig. 6 shows the comparison of motion in the vertical plane. Here we don't have as good agreement in the initial amplitude as in the horizontal plane. The vertical kick comes from the horizontal trajectory in the skew quadrupole elements (tilted quads or vertically displaced sextupoles) and/or from tilted kickers. Usually we assume we know skew quadrupole components in the model pretty well. But here the difference in the amplitude is about 20%, and we cannot be sure that we have the localized coupling error up to that accuracy. So it is hard to say what the source of the larger vertical oscillation is. Also, decoherence of the vertical motion looks completely different for the measurements and oscillations (right plot, bottom row). The only agreement here is that the decoherence time in the vertical plane is longer than in the horizontal plane.

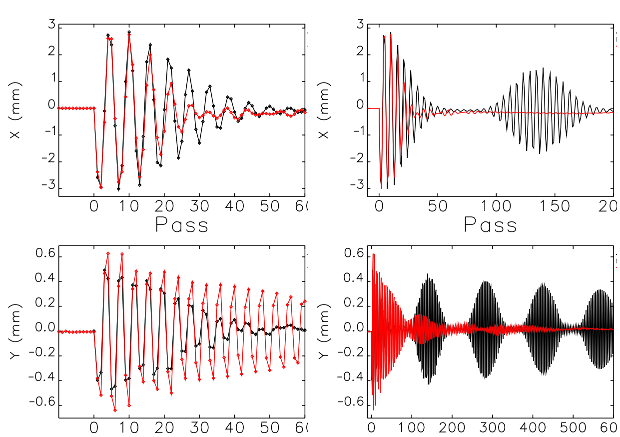

Figure 6: Comparison of the measured and simulated beam motion after injection. Top row is horizontal motion, bottom row is vertical motion. Red line shows measurements and black line shows simulations. Left column presents zoomed-in version of the right column.

Figure 7 compares measured horizontal tune shift with amplitude with the simulated one. The quadratic fit gives the following numbers for the tune shift with amplitude: simulated $-870mm^{-2}$; measured $-1100mm^{-2}$. The difference between the measured and the simulated value is a reasonable 20%. However, this difference cannot explain the significant discrepancy in the decoherence time found in Fig. 6. One thing that is not presented in our simulations is the wakefield effect that is known to affect the decoherence rate of the betatron oscillations. Simulation of the wakefield effect is more complicated and much more time consuming. We have attempted such simulations, and first results have shown shortening of the decoherence time but it was still longer than the measured values. We will continue this investigation.

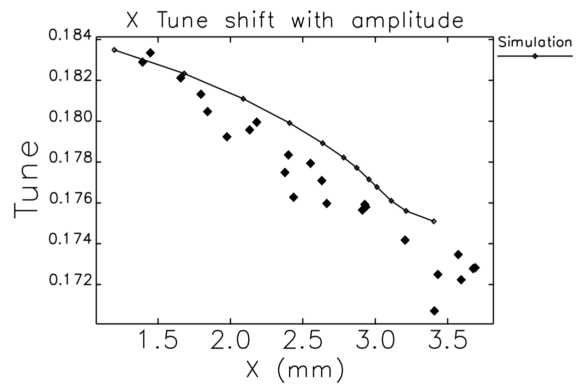

Figure 7: Comparison of the measured (symbols) and simulated (line) horizontal tune shift with amplitude.

CONCLUSIONS

We have demonstrated here one useful application of the new FPGA-based BPMs at APS: online monitoring of the betatron and synchrotron tunes using turn-by-turn beam motion induced by top-up injection. Due to very fast and changing decoherence rates, the tune and amplitude of the transverse motion is determined by fitting the data with several different equations and choosing the best fit results. Since during top-up the observed bunch experiences kicks with different amplitudes, the tune shift with amplitude can also be obtained online (only horizontal tune shift with horizontal amplitude can be measured with reasonable accuracy). The described procedure will be implemented for constant online archiving of the tunes.

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