NEW CHARACTERISTICS OF A SINGLE-BUNCH INSTABILITY IN THE APS STORAGE RING[*]

Chun-xi Wang and Katherine Harkay, ANL, Argonne, Illinois 60439 USA

Abstract

In the Advanced Photon Source storage ring, a transverse single-bunch instability has long been observed that appears unique to this ring. Many of its features have been previously reported. New results have recently been obtained using beam centroid history measurements and analysis. These preliminary results provide more detailed information regarding the characteristics of this instability and could provide insight into the physics mechanism.

INTRODUCTION

A new transverse single-bunch instability has been observed for several years in the Advanced Photon Source storage ring. It exhibits two distinctive modes: steady-state, with stable centroid oscillations, and bursting, with periodic burst-like oscillations [1]. At a certain threshold current, the beam starts a steady-state oscillation whose amplitude grows gradually with increasing current. When the current reaches a second threshold, the beam quickly transits into the bursting mode whose period and amplitude changes with increasing current. At even higher current, the beam can return to a steady-state oscillation. For a given machine condition, the entire sequence may not be observed before losing the beam. The physical mechanism of this instability is not clear yet. Many measurements have been taken to characterize this instability and the results were documented [1, 2]. Recently, more observations were made using Model-Independent Analysis of simultaneously recorded beam histories at hundreds of turn-by-turn beam position monitors (BPMs). Some of the findings are reported here. These results are far from systematic and complete, unfortunately, because of the difficulties in data acquisition and analysis caused by our faulty beam history system [3]. Nonetheless, these new observations provide further information on the characteristics of this unsolved instability. Since it is unsolved, we will describe the phenomena only and keep speculation to a minimum.

NEW OBSERVATIONS

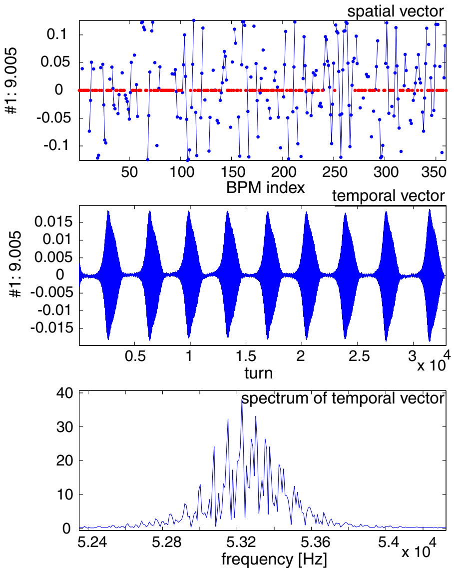

Figure 1: The first betatron mode of a bursting beam. From the top are the spatial vector, temporal vector, and Fourier spectrum of the temporal vector. Red dots are bad BPMs.

The basic technique used in the observations reported here are SVD mode analysis of 32 kilobyte turn-by-turn beam histories at close to 250 BPMs. Much information is obtained simply from the betatron modes [4], the first two dominating SVD modes due to betatron oscillation excited by the instability. Figure 1 shows an example of the first betatron mode from the histories of a bursting beam. The second betatron mode is similar to the first one (e.g., the temporal vector has the same spectrum and envelope but is 90° out of phase). The spatial vector is an orbit determined by the lattice, including effects such as wakefield. The temporal vector shows the bursting pattern, whose Fourier spectrum shows a broadened tune that is heavily modulated. The major modulating frequency is about 75 Hz, which is the bursting frequency. Note that the oscillation itself does not contain this frequency. Though outside this picture, two small synchrotron sidebands exist at ± 2.1 kHz, which is the synchrotron frequency.

Using the two betatron modes, we extract the action variable J_p for the centroid oscillation that better describes the bursting envelope. Corresponding to Fig. 1, Fig. 2 shows the turn-by-turn action variation and its Fourier spectrum that contains the bursting frequency and its harmonics. The maximum bursting amplitude has small variation from

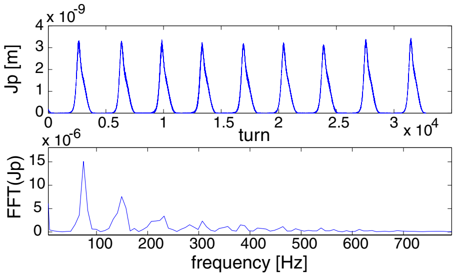

Figure 2: History of the action variable (bursting envelope).

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[*] Work supported by U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

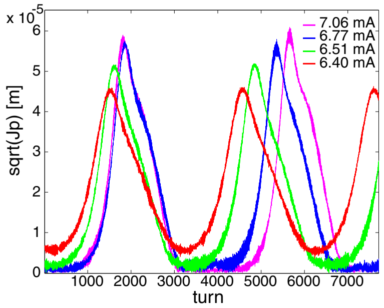

Figure 3: Bursting envelopes at four bunch currents. They are aligned at the middle between bursts.

burst to burst. The largest value is used to characterize the maximum bursting amplitude. The peak in the spectrum is used to determine the bursting frequency with a resolution of about 8 Hz (corresponding to 32kb histories and a revolution period of 3.68 μs).

Figure 3 plots $\sqrt{J_p}$ at four different currents under the same machine condition. Clearly both the bursting amplitude and frequency are changing with bunch current. As current decreases, both the bursting period and maximum amplitude decrease, while the minimum amplitude increases. At the transition from bursting to steady state with decreasing current, the bursts merge into the steady-state oscillation. (During these observations, we did not reach the second transition from bursting to steady-state with increasing current.) Note that the bursting period fluctuates slightly, which causes the first peaks at currents of 7.1 mA and 6.8 mA to suggest the same period while the second peaks suggest different periods.

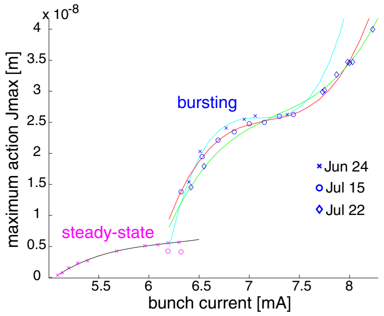

Figure 4: Dependence of instability amplitude (max. J_p of the centroid oscillation) on bunch current.

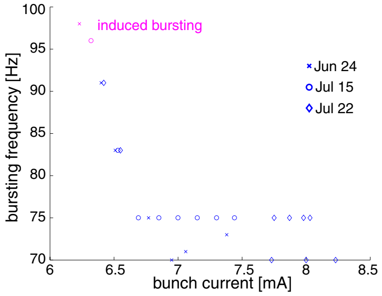

Figure 5: Dependence of bursting period on bunch current.

To better characterize the dependence of the maximum bursting amplitude and bursting frequency on the bunch current, we summarize measurements done on three different days at nominal rf voltage of 9.5 MV. In these measurements, we inject as much single-bunch current as possible, then record beam histories as the bunch current is reduced. Figure 4 plots the maximum action J_p versus current. The steady-state mode starts around 5.1 mA and the bursting mode starts around 6.35 mA. (In fact, the beam is still in the steady state at 6.5 mA on July 15. The blue circle data was obtained with induced bursting, as explained later.) We explored polynomial fitting to the data and found that, for both bursting and steady-state, a cubic fits each data set well (solid lines). The fitting parameters change slightly for the bursting data from different days. For the steady-state data, the cubic fit is better but the quadratic fit is acceptable. Of course, other fits (e.g., cubic of $\sqrt{J_p}$, which we checked) may work as well. More data are needed to reduce uncertainty. Similarly Fig. 5 plots the bursting frequency versus current. The frequency decreases more or less linearly with increasing current around the bursting threshold, but runs into a wall at about 75 Hz and stays the same thereafter.

We also briefly investigated how the bursting amplitude and frequency depend on the horizontal chromaticity ξ_x during one of the shifts. The result for amplitude verse ξ_x is plotted in Fig. 6. The frequency stayed the same while ξ_x was changed from 6 to 4. The current lost from 7.4 to 7.2 mA during the data collection. The effect of this current change is negligible since both amplitude and frequency do not vary much around this current. More measurements are needed to further characterize the effect of horizontal as well as vertical chromaticity.

For a fixed beam current, the peak amplitude of the bursts was found to depend strongly on the amplitude-dependent tune shift. By varying the harmonic sextupoles, the horizontal tune-shift-with-amplitude was varied by about 25% compared to the nominal value (the chromaticity changes are minimal). The peak amplitude decreases proportionately when the amplitude-dependent tune shift is increased, and visa versa. This is expected and is shown in Fig. 7. Note the burst period also changes. This observa-

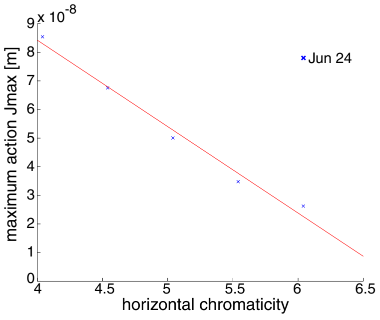

Figure 6: Dependence of burst amplitude on chromaticity.

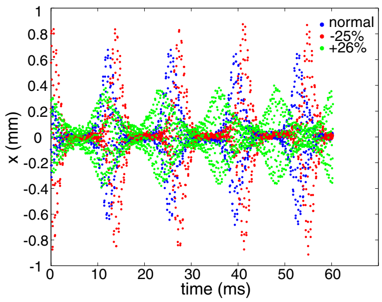

Figure 7: Bursting patterns at three tune-shift-with-amplitudes. The currents are 8.1, 8.2, 7.9 mA, respectively.

tion was done much earlier with a "high-emittance" lattice.

Besides the steady and bursting states, a very interesting transient behavior was observed when a steady-state beam was kicked transversely. Figure 8 shows such an example. Before the kick, the bunch centroid undergoes steady-state oscillation; right after the kick, the centroid oscillation quickly decoheres to a much lower amplitude just as a stable bunch will do; shortly afterward, a bursting oscillation amazingly appears and gradually merges back to the steady-state oscillation. A few of the bursting amplitudes and periods in the previous figures are extracted from such an induced bursting transient. If the beam current is far from the bursting threshold, the decohered bunch will gradually return to steady-state oscillation without bursts.

All the above observations are based on the two betatron modes in SVD mode analysis. There are a few more significant modes above the noise floor. Typically, the third largest (but much smaller than the first two) mode is the synchrotron mode, which exists even when the beam is stable [5]. In the bursting state, the fourth largest mode usually is a very special mode due to bursting instability. Figure 9 shows this mode using the same history data as was used in Fig. 1. The temporal vector and its spectrum show periodic oscillations with the same period as the bursting mode. The spectrum is dominated by the bursting frequency and its harmonics and has little horizontal betatron frequency (this is the only mode that has such a feature). It is interesting to note that the bursting peaks correspond to the zero-crossing points (one of the two in each period), i.e., when bursting reaches maximum amplitude this mode reaches zero, and visa versa. Another significant feature of this mode is its spatial vector, which peaks at the middle (between the straight sections) of each of the 40 sectors in the ring (the irregularity in the spatial pattern is due to bad BPMs), where the beta function and the first- and second-order dispersions are large. However, this spatial pattern is not the beta function or the first-order dispersion. It could be the second-order dispersion but there are no significant synchrotron oscillations in the spectrum of the temporal vector. At this point, this mode is as mysterious as the instability itself.

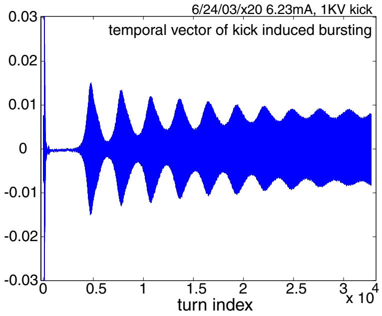

Figure 8: Kick-induced transient bursting behavior in steady state near the bursting threshold.

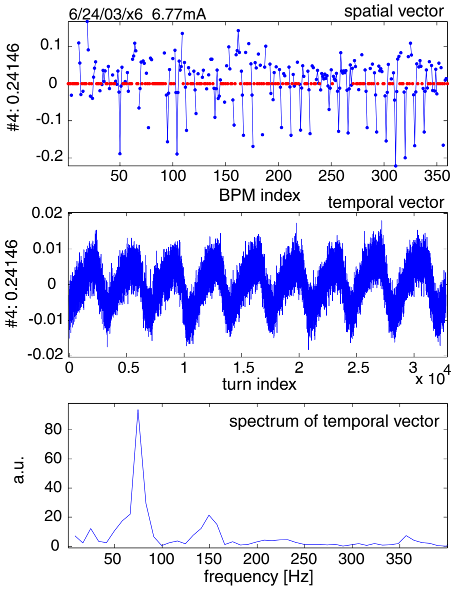

Figure 9: A special mode due to bursting instability. The mode number and its singular value are shown on the left.

Until very recently, the bursting behavior was only observed in high-current single bunches spaced at large intervals ($> 54\lambda$, where λ is the rf wavelength.) Remarkably, bursts have now also been observed with multiple bunches spaced at 1 or 4λ. The horizontal chromaticity needed to stabilize the beam decreased markedly when smaller fractions of the ring were filled, keeping the total current fixed (100 mA). The bursting instability appears to be a robust beam response to possibly different sources of instability.

Special thanks to E. Crosbie for calculating the coefficients of the amplitude-dependent tune shift.

REFERENCES

[1] K. Harkay et al., Proceedings of the 2001 Particle Accelerator Conference, p. 1915 (2001).

[2] K. Harkay et al., Proceedings of the 1999 Particle Accelerator Conference, p. 1644 (1999).

[3] Chun-xi Wang et al., Proceedings of the 2001 Particle Accelerator Conference, p. 1355 (2001).

[4] Chun-xi Wang, Proceedings of the 2003 Particle Accelerator Conference, p. 3407 (2003).

[5] Chun-xi Wang, ibid., p. 3410 (2003).