TRANSVERSE SAWTOOTH INSTABILITY AT THE ADVANCED PHOTON SOURCE*

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Abstract

A detailed investigation has been made of the transverse sawtooth instability observed at the Advanced Photon Source. This horizontal single-bunch instability exhibits two modes: steady-state, with continuous centroid oscillations at fixed amplitude, and bursting, with an amplitude that varies quasi-periodically with a peak-to-peak excursion of up to 2 mm. The transition between modes is sharp and, depending on machine conditions, multiple transitions are observed with increasing bunch intensity. The threshold and character of the instability also vary with chromaticity and rf voltage. The horizontal instability shows striking similarities to the longitudinal sawtooth instability observed in the Stanford Linear Collider damping ring, as well as clear and obvious differences. This paper presents experimental results and a possible mechanism for the sawtooth instability that is suggested by simulations.

1 INTRODUCTION

For typical 100-mA multibunch user operation at the 7-GeV Advanced Photon Source (APS) electron storage ring, single-bunch intensities are limited (in practice) to under 5 mA to maintain beam lifetimes over 20 h. Ideally, the physical intensity limit is well above operational constraints. With two 5-m-long, 5-mm-gap vacuum chambers (v.c.) and 18.5 8-mm-gap v.c., a maximum single-bunch intensity of 11 mA has been achieved. Well below the intensity limit and above the mode-coupling threshold, a transverse single-bunch sawtooth instability is observed [1]. In electron storage rings, sawtooth instabilities have long been observed longitudinally. More recently, either transverse sawtooth [2] or steady-state oscillations [3] have been observed for negative chromaticities. The APS instability appears unusual in that both sawtooth and steady-state oscillations are observed in the transverse plane with large positive chromaticities.

Detailed parametric experimental studies were performed to characterize the transverse sawtooth instability. Simulations performed to date reproduced some, but not all, of the instability characteristics. Various impedance models and the single-bunch intensity limit are examined.

2 MEASUREMENTS

Measurements of the beam were carried out using beam position monitors (BPM) and photon diagnostics. Data from the BPMs were acquired by using turn-by-turn x-y beam histories (3.68 μs/turn). Correlations of the instability with beam size, energy spread, and bunch length were performed by using data acquired from two photon beamlines.

Machine parameters found to most influence the transverse instability are: beam intensity (I_b), rf voltage (V_{rf}), and chromaticity ($\xi = \Delta\nu/\Delta p/p$). The instability threshold (onset) depends strongly on ξ_x and only weakly on V_{rf}. The instability growth rates and mode transitions depend strongly on ξ_x. Finally, the bursting-mode amplitude is strongly dependent on V_{rf}, whereas the steady-state amplitude is only weakly dependent on V_{rf}. Observation details are discussed below.

2.1 Intensity and V_{rf} Dependence

Low-dispersion BPM histories for varying beam intensities are shown in Figs. 1 and 2 for 9.4 MV (nominal) and 7.3 MV rf voltages, respectively. The horizontal centroid offset (< x >) is shown on the vertical axes. The nominal chromaticities were (3.2, 6.4), where the parentheses indicate ξ_x and ξ_y, in that order. The intensity val-

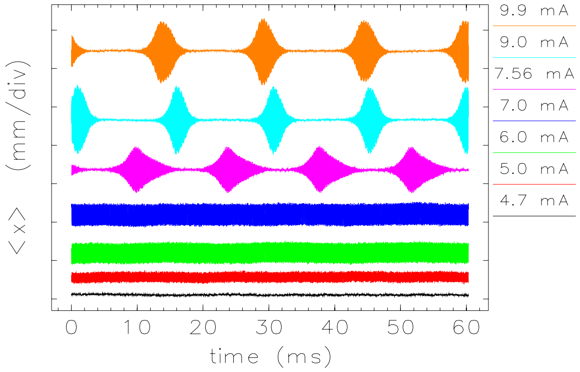

Figure 1: Single-bunch horizontal BPM histories, 9.4 MV.

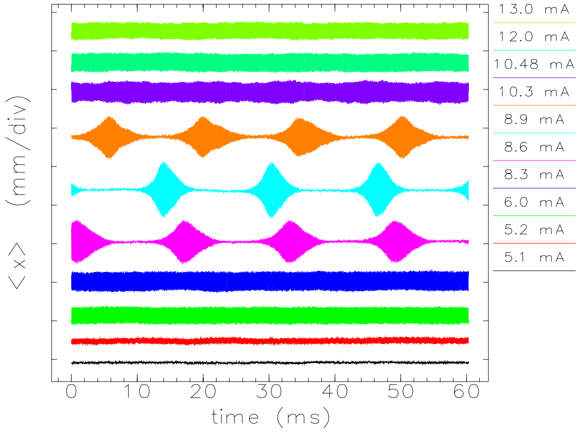

Figure 2: Single-bunch horizontal BPM histories, 7.3 MV.

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ues span a range from just below the onset of the instability (bottom) to the intensity limit (top) (only one 5-mm-gap v.c. was installed at the time of these measurements). The thick bands indicate continuous centroid oscillations at a fixed, saturated amplitude, termed the "steady-state" mode. The sawtooth-like pattern indicates quasi-periodic growth and decay of centroid oscillations, termed the "bursting" mode. During either mode, a self-excited horizontal betatron spectral line was observed using a stripline pickup.

The bursting mode rise and decay rates are not at all linear with intensity. For fixed chromaticity, the bursting period is rather constant. The transition between steady-state and bursting modes is typically sharp. For lower V_{rf}, there is a transition back to steady-state before the beam intensity limit is reached. Fig. 2 looks remarkably like Fig. 4 in Ref. [4], except that at the Stanford Linear Collider damping rings, the instability is longitudinal. Despite the obvious differences, both machines exhibit nonlinear behavior of collective effects that are qualitatively similar.

For varying V_{rf}, different effects are seen in the oscillation saturation amplitude, illustrated in Fig. 3. In the steady-state mode, the amplitude rises and then reaches a limit with increasing I_b. The limiting amplitude and instability onset vary only slightly with V_{rf}. The effect on the amplitude in the bursting mode, however, is more dramatic. The saturation amplitude does not rise monotonically with either I_b or V_{rf}. Notably, the intensity limit does not necessarily occur at the largest centroid oscillation. In fact, at the lower voltage (7.3 MV in Fig. 3), the beam reverts to steady state at half the peak amplitude before the limit is reached. The intensity limit is almost proportional to the bunch length when V_{rf} is varied (47 ps at 9.5 MV and 68 ps at 7.1 MV [5]), implying an invariant peak intensity limit (see also Section 3.2).

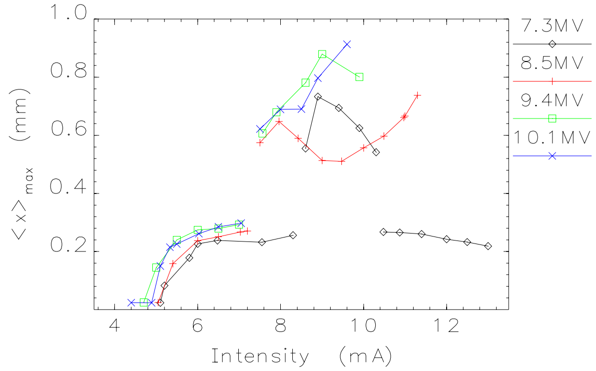

Figure 3: Maximum amplitude of bunch centroid oscillations as a function of rf voltage. Bursting mode occurs from 7–10 mA; otherwise, steady state occurs.

2.2 Chromaticity Dependence

The effects of changing the chromaticity are illustrated in Fig. 4 (9.4 MV and two 5-mm-gap v.c.). The transitions from stable to horizontal steady-state to bursting modes are sensitive to changes in ξ_x only; they were unaffected by changes in ξ_y. The bunch-intensity limits, however, change in both cases. Prior studies indicate that the instability growth rate is inversely proportional to ξ_x [1]. Consequently, at a fixed I_b, the bursting period decreases and the saturation amplitude increases when ξ_x is reduced (not shown). When ξ_y was decreased to 3.3, a **vertical** steady-state instability was seen, accompanied by a self-excited vertical betatron spectral line.

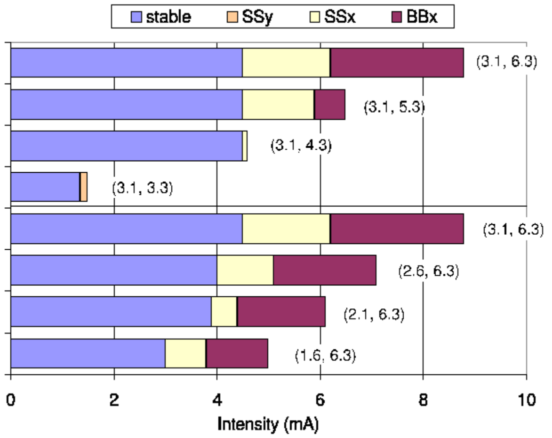

Figure 4: Instability mode transitions and beam intensity limits vs. chromaticity. Top: ξ_y is varied; bottom: ξ_x is varied (SS=steady-state; BB=bursting) (9.4 MV).

2.3 Beam Size vs. Instability Amplitude

The beam size was measured at two pinhole photon beamlines located at high and low dispersive points, respectively. Fast imaging techniques were used to reduce the "blur" caused by beam centroid motion. In the first setup, gated intensified cameras were used with exposure times of 3 µs, capturing beam images in a single pass. In the second setup, a high-speed CMOS camera was used to capture the time evolution of the beam size, with exposure times of 220 µs taken at a rate of 4000 frames / s. The total length of the imaging record is 2000 frames (0.5 s).

Using the first setup, the emittance (ε) and relative energy spread (δ) were extracted from the two sets of turn-by-turn beam size data using the measured lattice function values at each source. The results were then averaged and are shown in Fig. 5 for the nominal chromaticity. At the instability threshold, δ grows by 30% up to the intensity limit. During the steady-state mode (5–7 mA), ε grows by 30% and appears to follow the maximum average offset

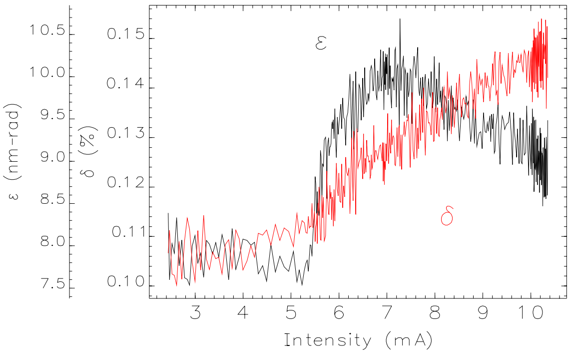

Figure 5: Measured horizontal emittance and energy spread vs. bunch intensity (7.0 MV, nominal $\xi_{x,y}$).

shown in Fig. 3. The beam does not decohere completely; rather, it seems to behave like a rigid bunch.

Using the second setup, the bunch evolution over the bursting mode could be studied. Initial observations indicate that the beam size blows up over a burst, but not to the full oscillation amplitude. The beam size then damps down before the next burst. A preliminary analysis of the betatron tune during the bursting mode shows that the tune at the onset of a burst is different from that during and after the burst. More detailed analyses are planned to relate the tune shift to the saturation amplitude and bursting period.

3 DISCUSSION

3.1 Impedance Modeling

The APS broadband impedance can be categorized into two parts: the geometric impedance caused by transitions from the normal aperture to the small-gap v.c., and the resistive wall impedance of all small-gap v.c. While the geometric impedance contributes mostly to the vertical broadband impedance caused by sharper vertical transitions, the resistive wall impedance of an elliptical chamber contributes almost equally in both the horizontal and the vertical planes [6]. It is estimated that the broadband contribution of the small-gap v.c. total resistive wall impedance is on the order of $0.1\ \mathrm{M\Omega/m}$ in both planes, comparable to the horizontal broadband resonator (BBR) model but much less than the vertical BBR used in Ref. [1]. A local bump method [7] was used to distinguish these two types of impedance experimentally.

Thus, both the BBR impedance and the resistive wall impedance [8] are simulated in the program *elegant* [9] to model the horizontal instability observed at the APS. A longitudinal BBR impedance (Q=1) of cutoff frequency 25 GHz and shunt impedance 15 kΩ is also included in the simulation to model the bunch lengthening with increasing intensity. Preliminary simulation results suggest the following mechanism for the horizontal sawtooth instability: the beam centroid motion becomes unstable after the horizontal mode-coupling instability threshold (typically between 3 and 4 mA). The instability is self-limited as the beam filaments and the emittance grows, leading to Landau damping of the centroid oscillation. Eventually, radiation damping brings the enlarged beam back to the original condition, and this cycle repeats. Such a correlated beam centroid and size enlargement are also suggested by the beam size measurement described in Sec. 2.3. However, the transition to bursting from the steady-state mode and sometimes back to the steady-state mode with current has not been reproduced in these simulations.

3.2 Single-Bunch Intensity Limit

One motivation for the present study is to understand the mechanisms limiting the single-bunch intensity at the APS. At low, positive ξ_y (ξ_x), the transverse mode-coupling instability (TMCI) determines the intensity limit of 2 mA (4.5 mA) [1], as also indicated in Fig. 4. At higher, positive ξ_x and ξ_y, the TMCI threshold can be exceeded without any beam loss. Instead, the beam manifests the steady-state amplitude oscillation or the bursting behavior.

The observed single-bunch intensity limit was compared to the post head-tail (PHT) theory [10] that predicts a fast vertical instability setting the intensity limit at sufficiently high chromaticity. Using the effective impedance fitted from the tune shift with intensity [1], the theoretical PHT limits are around a factor of 3 higher than the experimental ones at various ξ_x and ξ_y.

Installation of the first 5-mm small-gap chamber did not measurably change the tune shift with intensity in either transverse plane; however, the single-bunch intensity limit dropped by about 25%. With the 5-mm v.c. temporarily removed, a study using vertical scrapers was conducted to mimic the effects of the 5-mm gap. If the scrapers were closed to a 5-mm gap after the maximum beam was stored, no obvious effect on the intensity limit was observed. If the scrapers were inserted and then the beam was injected, the single-bunch current limit dropped by 25%. This experiment strongly suggests that the single-bunch intensity limit at APS is related to the injection process. Because the beam is injected horizontally off the closed orbit, a plausible explanation is that the x-y coupling, together with the vertical impedance, give rise to a vertical instability that would not normally exist for a stored beam. At the intensity limit, the beam hits the physical vertical aperture of 5 mm and cannot be further accumulated. Based on this experiment, we hypothesize that it is the small-gap vacuum chambers and the injection process that limit the APS single-bunch intensity, rather than the PHT effect.

4 ACKNOWLEDGMENTS

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