TRANSVERSE MULTIBUNCH BURSTING INSTABILITY IN THE APS STORAGE RING*

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Abstract

The horizontal bursting instability was first observed in a single bunch in the Advanced Photon Source (APS) soon after operation began. Above the instability threshold, the bursting is characterized by exponentially growing bunch centroid oscillations whose amplitude saturates, then decays, repeating quasi-periodically. More recently, bursting was also observed with multiple bunches in both the horizontal and vertical planes, showing that this is not purely a single-bunch phenomenon. On the other hand, the multibunch instability threshold is strongly dependent on bunch spacing, and the dependence is markedly different for the two transverse planes. Depending on the bunch spacing, the bunch-to-bunch oscillations are sometimes coupled, sometimes not. In this paper, we discuss the threshold in terms of the chromaticity required to stabilize the beam. We present instability imaging data using a streak camera that shows the bunch-to-bunch oscillation phase, and turn-by-turn beam position histories that give the bursting time dependence for different bunch spacings. Finally, we discuss the machine impedance and measured tune shift with current.

INSTABILITY THRESHOLD

The multibunch bursting phenomenon is qualitatively similar to single bunch [1-3]. At the stability threshold in the horizontal plane, we observe the onset of the steady-state (SS) instability, characterized by emittance growth, a self-excited betatron tune signal, and centroid oscillations with constant amplitude. The bunch phases are coupled. At lower chromaticity, the onset of the bursting (B) instability is observed. At the instability threshold in the vertical plane, x-y coupling growth is typically observed before a self-excited vertical tune or centroid oscillations can be seen. The bunch phases are apparently not coupled, at least for the standard 24-bunch operating mode; rather, individual bunches become unstable. Also, vertical bursting is often but not always observed (the vertical bursting mode is more difficult to observe with single bunch).

With 100-mA beam stored in different uniform bunch patterns, the chromaticity $\xi = \Delta\nu/\delta$, where ν is the tune and δ is the relative momentum spread, in each plane was varied while keeping the chromaticity in the other plane fixed around 6-7. The bunch intensity was as uniform as possible. The tunes were (0.2, 0.26) and the rf voltage was 9.0 MV. In the horizontal plane, the most sensitive indication of instability onset was an emittance blowup observed on an x-ray pinhole camera. The turn-by-turn beam position monitor (BPM) beam history (BH) shows that the blowup is largely due to centroid motion. For consistency, the SS threshold was defined to occur when the emittance blowup was about 20%. In the vertical plane, the threshold was defined to occur when the coupling grew from ~1% to ~1.5-2%. At this point, a self-excited vertical tune signal was just visible above the noise. The BH typically did not show obvious centroid motion at this level. As we shall see later, we cannot call the vertical instability onset an SS instability. In both planes, the B threshold was defined when bursting was observed on the BH. The bursting modulation was typically 100%, but not in all cases.

Figure 1 shows the chromaticities corresponding to the instability onset and the bursting instability threshold in both planes. The data were repeated for 24, 48, 81, and 324 bunches. The rms error bars are small with the exception of 24 bunches in the vertical plane. We could not obtain data for 36 bunches: rf cavity higher-order mode (HOM) damper heating limited the current to 50 mA.

From 324-1296 bunches the threshold in both planes is inversely proportional to the bunch current. This is consistent with the increased head-tail damping for higher bunch current [4]. From 24-54 bunches, the threshold appears to be dominated by another mechanism, likely single-bunch effects. The horizontal onset is consistently 1-2 units above the vertical. There is a curious deviation from these trends for 72-162 bunches. The horizontal onset reaches a minimum at 108 bunches, whereas the vertical onset exceeds the horizontal, peaking at 81 bunches.

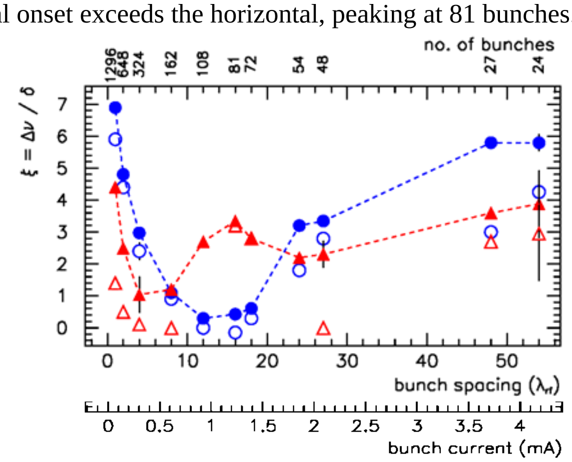

Figure 1: Horizontal (●) and vertical (▲) chromaticity thresholds as a function of bunch spacing, in units of 2.84 ns. The closed symbols give the instability onset and the open symbols the bursting threshold. The bunch number and bunch current are indicated (100 mA total).

BUSTING MODE

In the horizontal plane, the bursting threshold is about one ξ unit below the instability onset. In the vertical plane, the bursting threshold was more variable: ξ was either near or equal to the onset (72, 81 bunches), near zero (48, 162 bunches), or nonexistent (54, 108 bunches).

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Figure 2 shows beam histories for 24 bunches undergoing the bursting instability. The burst rise and fall times, noted on the figure, were computed by fitting the bursts to the function $C + A\exp(Rt)$. The rise fit rate R = (G – D) is the instability growth rate G less the radiation damping rate D = (9.63 ms)$^{-1}$. The fall time is a function of radiation damping, nonlinear detuning, chromatic decoherence, head-tail damping and, of course, the wakefield [5,6]. These effects are not analyzed here (only D is included), but are accounted for in simulations of a vertically kicked single bunch in APS in Ref. [7]. Experimental studies of multibunch decoherence are ongoing [8]. The amplitude and rise time of the bursting instability in the two planes are within 30%, although the period (12 vs 31 ms) and fall times are quite different, likely due to the chromaticity.

The bursting behavior shows large variations for different bunch patterns, bunch current, and chromaticity (see Fig. 3). For bunches more closely spaced than the usual 150 ns (for 24 bunches), individual bunch signals overlap due to a 10-MHz bandpass filter at the BPM receiver input. For 324-bunch operation, for example, the BH gives a weighted average of about a dozen bunches. The horizontal bursts appear to be more periodic than the vertical in the examples shown, but this is not strictly the case.

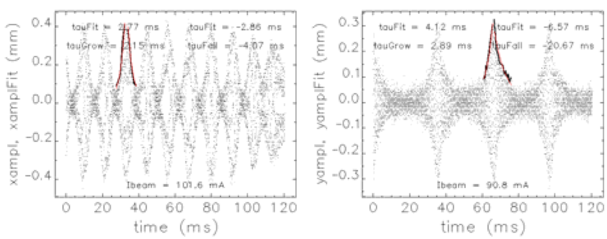

Figure 2: Centroid oscillations for bursting beam, 24 bunches; horizontal (left, ξ_x 4.6) and vertical (right, ξ_y 1.9).

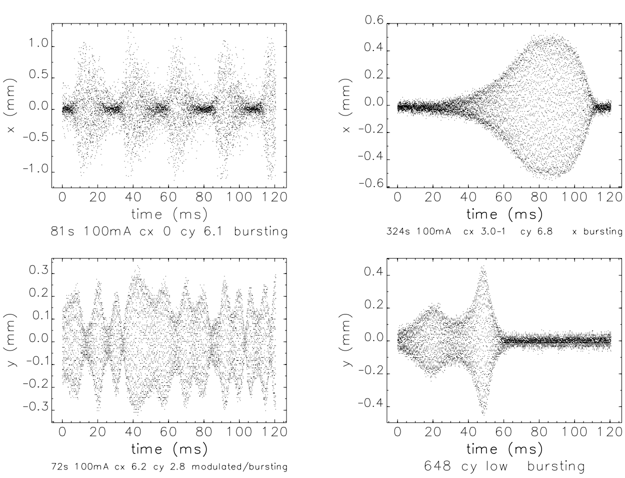

Figure 3: Bursting mode BHs for various bunches; approx. ξ noted (horizontal on top, vertical on bottom).

STREAK CAMERA IMAGING

We used a dual-sweep streak camera (sector 35 diagnostics bending magnet source) to determine whether the bunch-to-bunch motion is coupled or not. In the horizontal plane, for 24, 162, 324, and 648 bunches, the bunch centroid motion is coupled, with mode number ~0.8, for both the steady-state and bursting modes. Data for 324 is shown in Fig. 4 for top view (x-t). In the streak image, the fast sweep (vertical axis) full scale is 20 μs (5.4 turns), while the slow sweep (horizontal axis) full scale is 10 ms.

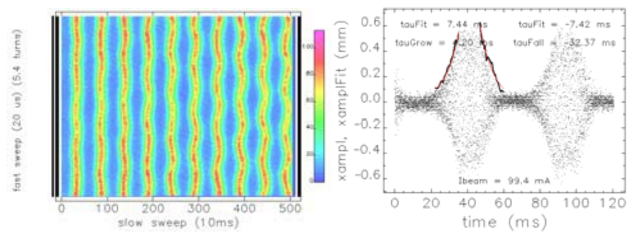

Figure 4: 324 bunches, dual-sweep streak image (left) and BH (right). Streak image captures onset of burst. Burst rise time is 4.2 ms, burst period is 53 ms, ξ_x 1.1.

In the vertical plane, we have only imaged 24 bunches. At the instability onset, individual bunches become unstable: first one, then more as ξ is lowered. The beam size is blown up, and some head-tail-like oscillation can be seen. The unstable bunches appear weakly coupled, sometimes oscillating in phase, sometimes not. The highest-current bunch is the last to become unstable, presumably due to the larger head-tail damping or tune shift. An unstable bunch can be stabilized by injecting more current into it. Figure 5 shows synchroscan streak images for side-view (y-t). The image at the left shows the instability onset, where a single bunch goes unstable (100 mA). Note the large beam size blowup, and no obvious collective motion. There was no beam loss in this case. After lowering ξ_y too far, ~35mA was lost; the corresponding streak image is shown in the figure. Head-tail motion can be seen in some of the unstable bunches. The coupling registered as 140%. The lone stable bunch has about 20% more current than the others. We stabilized one of the unstable bunches by injecting 20% more current into it, confirming the current dependence. Interestingly, the stable bunch can be made unstable either by lowering ξ_y further, or by driving the beam with a vertical kicker (presumably kicking charge out). Remarkably, when the bunch current is near the single-bunch TMCI threshold of ~1.7 mA and the chromaticity is ~4, the unstable bunches can be stabilized by pinging the beam with the horizontal kicker. This observation is not sensitive to the bunch spacing or gaps, so it does not appear to be explained by ion trapping.

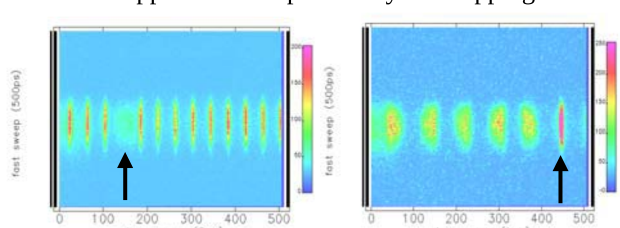

Figure 5: 24 bunches, vertical instability onset (left, 100 mA; unstable bunch marked) and with lower ξ and beam loss (right, 65mA). Lone stable bunch (marked) has ~20% more current than the others.

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TUNE SLOPE MEASUREMENTS

Measurement of the betatron tune shift as a function of current is often used to estimate the transverse impedance of storage rings. Figure 6 shows measurement results for 24 bunches, the most commonly used bunch pattern at APS. One can see that the horizontal tune slope is positive. This was recently observed at several rings [9,10] and is explained by a quadrupolar wakefield of non-symmetric vacuum chambers. APS has a large number of small-gap insertion device vacuum chambers that are basically open from one side in the horizontal plane.

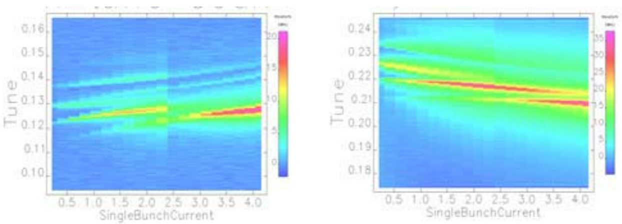

Figure 6: Tune shift with single bunch current for 24 bunch fill pattern; total current was changed from 10 to 100 mA (horizontal tune shift on left, vertical on right).

The tune shift as a function of single-bunch current was measured for different uniform bunch patterns. For each bunch pattern the current was scanned from 100 mA down to 10 mA except for two- and one-bunch fills where current was limited by a single bunch limit. The results are presented in Table 1 and in Fig. 7.

Table 1: Tune Shift with Single Bunch Current for Different Uniform Bunch Patterns

N bunches	Bunch separation (μs)	X slope	Y slope
1296	0.003	0.066	-0.036
324	0.011	0.021	-0.012
108	0.034	0.0076	-0.0049
24	0.153	0.0013	-0.0031
2	1.84	-5e-5	-0.0028
1	3.68	4e-4	-0.0025

The table shows that the tune slopes are approximately inversely proportional to the bunch spacing (linear with the number of bunches) for short distances between bunches. The horizontal tune slope is positive for all bunch patterns. The accuracy of the horizontal tune slope measurement for one- and two-bunch patterns was of the order of the slopes themselves, so we can only say that the tune slope for those conditions was close to zero.

DISCUSSION

A multibunch bursting instability is observed in both the horizontal and vertical planes at the APS, but exhibits considerable variation in the onset and dependence on beam conditions. The horizontal instability is coupled-bunch with bursting centroid motion and minimum beam size blowup. The vertical instability appears to mostly involve beam size blowup and possibly, weak coupling of the centroid motion. Considering all the bursting data, it

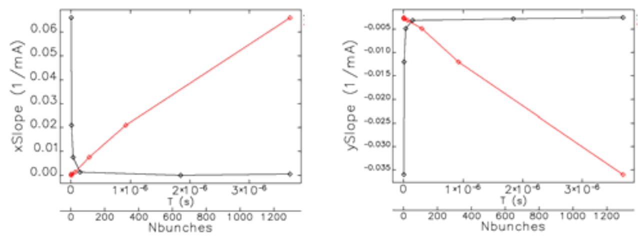

Figure 7: Horizontal (left) and vertical (right) tune slope dependence on the bunch spacing (black curves). Same slopes are also plotted vs. total number of bunches (red curves) to show that the curves are approximately inversely proportional to the bunch spacing (i.e., proportional to the number of bunches).

appears as though the burst rise times and periods are roughly proportional. A linear fit gives a slope of 10 ±6.

The instability threshold is either proportional (widely-spaced bunches) or inversely proportional (closely-spaced bunches) to the bunch current. Curiously, for bunch spacings between these extremes, the behavior in the vertical plane deviates from these trends. We compared 50 and 100 mA and found that the thresholds are not simply related to the bunch current or spacing. We also studied nonuniform fills. A beam with a gap and 1-2 λ_{rf} bunch spacing is horizontally more stable. The vertical plane is largely insensitive to a gap. Several of these observations were reported for multibunch instabilities at ESRF [10].

The tune slopes were measured for several uniform bunch patterns. The signs of the tune slopes are consistent with other rings with asymmetric vacuum chambers. The instability threshold appears to be proportional to the tune slope for closely-spaced bunches, but more analysis is required to understand all the data. Short-range transverse wakefields have been analyzed extensively at APS [7], and analysis of the long-range wakefields (resistive wall, in particular) is planned. The quantitative results can then be compared with the ESRF, for example [10,11,12].

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