COMPENSATION OF LONGITUDINAL COUPLED-BUNCH INSTABILITY IN THE ADVANCED PHOTON SOURCE STORAGE RING

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Abstract

A longitudinal coupled-bunch (CB) instability was encountered in the 7-GeV storage ring. This instability was found to depend on the bunch fill pattern as well as on the beam intensity. The beam spectrum exhibited a coupled-bunch signature, which could be reproduced by an analytical model. The oscillations were also observed on a horizontal photon monitor. The beam fluctuations exhibited two periodicities, which were found to be correlated with the rf cavity temperatures. This correlation is consistent with the measured temperature dependence of the higher-order mode (HOM) frequencies [1]. The HOM impedance drives the beam when brought into resonance with the CB mode by the temperature variation. Increasing the inlet cavity water temperature suppressed the instability. The experimental results are compared to an analytical model which characterizes the fill-pattern dependence. Studies to identify the offending HOMs are also presented.

1 INTRODUCTION

The Advanced Photon Source (APS) is a national facility that produces brilliant x-rays for use in scientific and industrial research. Selected parameters for the 7-GeV positron storage ring (SR) are found in Table 1. The nominal stored current is 100 mA, with a design goal of 300 mA. A variety of bunch fill patterns have been employed to meet the needs of the x-ray users and to optimize performance of the beam position monitors (BPMs) in orbit control. Typically, between 40 and 200 bunches are stored out of a possible 1296. It was discovered that some of these fill patterns give rise to a longitudinal CB instability.

Table 1: Nominal APS Storage Ring Parameters

Circumference		1104	m
Revolution frequency	f_{rev}	271.55	kHz
Harmonic number	h	1296	
rf frequency	f_{rf}	351.927	MHz
rf gap voltage	V_{rf}	8.5 - 9.5	MV
Bunch length, FWHM		100	ps
Synchrotron frequency	f_s	1.8 - 2.0	kHz
Synch rad. energy loss /turn	U	5.45	MeV
Damping time, longitudinal	τ_D	4.73	ms

The coupled-bunch instability is an intensity-dependent collective effect that is driven by long-range wakefields such as those produced in the excitation by the beam of high-Q HOMs in the rf accelerating cavities. Under appropriate resonance conditions and with sufficient current, growing beam fluctuations develop, possibly resulting in beam loss. The oscillations occur at harmonics of the synchrotron frequency, modulating specific rotation harmonics in the frequency spectrum of the beam current. There are $\pm$ h/2 possible coupled-bunch modes, n, in which the phase of the ν^{th} bunch is $2\pi n\nu/h$. When the instability was first encountered in the SR, the oscillation amplitude was found to be cyclical, growing and decaying over several minutes. It was quickly found that the amplitude variations correlated closely with temperature variations in several rf cavities. The experimental observations and instability compensation are described first. Following is a discussion of the likely driving rf cavity HOM and characterization of the unstable fill patterns.

2 OBSERVATIONS

The SR beam spectrum was observed using the raw signal from a non-zero dispersion BPM button, and the transverse beam size and centroid motion were observed using a bending magnet x-ray pinhole diagnostic signal. The pinhole signal is processed in real-time at a rate less than f_s; therefore, synchrotron oscillations result in an effective horizontal beam size growth. For unstable fill patterns, the beam lifetime was markedly poor, and 100 mA typically could be reached only with difficulty due to beam losses during injection. The particular bunch fill pattern is denoted as M×N, where M is the number of groups, or trains, of N consecutive bunches in a train. The bunch trains can be placed in a symmetric or asymmetric configuration around the ring.

Beam spectra for a symmetric, 4×12 bunch pattern are shown in Figs. 1 and 2, cycling between a stable and unstable state, respectively. A span of one f_{rf} is shown at a high harmonic, since the peak of the CB signals are near (bunch length)$^{-1}$. The beam current is about 100 mA. The envelope of a model 12-bunch train matches the envelope of the rotation harmonics of the data in Fig. 1. The unstable beam spectrum exhibits a coupled-bunch signature. When an interbunch phase advance corresponding to a CB mode of n=

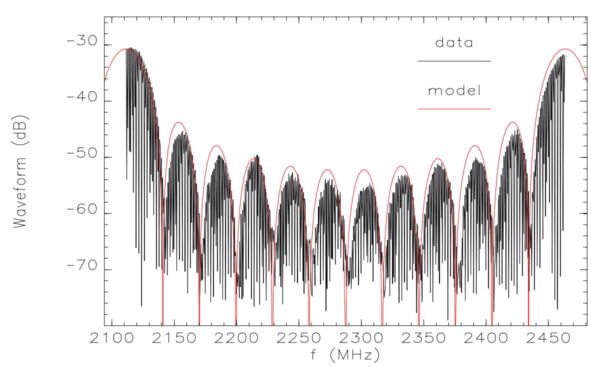

Figure 1: Stable beam spectrum, 4×12 bunch pattern.

540 was introduced in the crude model, using a maximum displacement of 7 degs of rf phase (55 ps), the result shows qualitative agreement with the data in Fig. 2.

In a uniformly-filled ring, the CB spectrum is periodic in $f_{rf}/2$. When the fill pattern is non-uniform, the CB spectrum is highly degenerate. Synchrotron sidebands from several CB modes may be aliased onto every revolution harmonic. This is evidenced in the asymmetric pattern of f_s sidebands in Fig. 3 for the unstable 4×12 fill pattern.

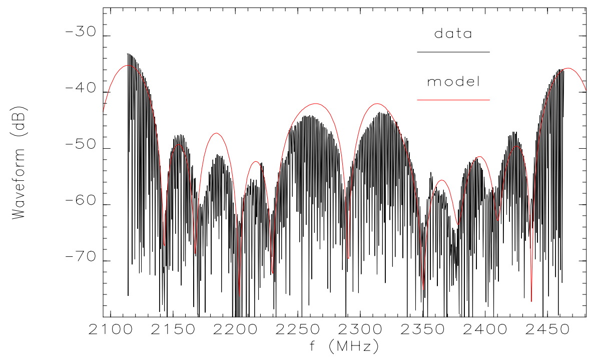

Figure 2: Unstable beam spectrum, 4×12 bunch pattern.

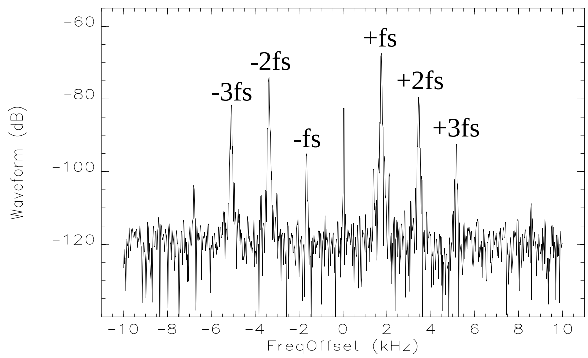

Figure 3: Unstable beam spectrum, centered at $7f_{rf} + f_{rev}$.

2.1 Correlation with Rf Cavity Temperature

The cyclical nature of the longitudinal oscillations is seen in Fig. 4, which shows the apparent horizontal beam size over two hours for an unstable fill pattern during a 100-mA store. The maxima correlate with the CB signal in Fig. 2. The beam current decays to 85 mA during this time; the CB fluctuations persist below 75 mA. Two distinct periodicities are seen: 3-4 min and 15-20 min. Little motion is seen in the horizontal centroid or in the vertical plane.

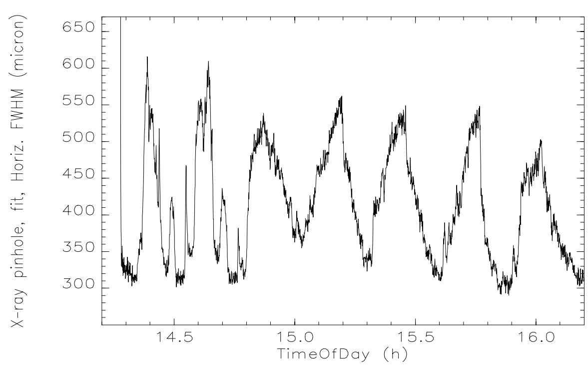

Figure 4: Fluctuating horizontal beam size, 100-mA store.

The rf cavity center temperatures in two of the four sectors over the same period reveal in Fig. 5 a direct correlation with the horizontal beam size variations. This observation is consistent with the view that the HOM frequencies are shifting into and out of resonance with a beam harmonic as the cavity temperatures vary. The measured temperature variation of the HOM frequencies is reported in Ref. 1.

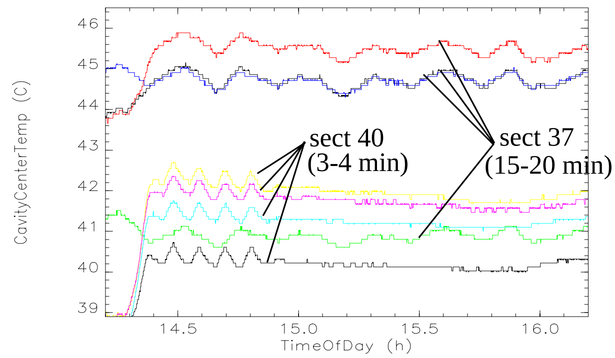

Figure 5: Rf cavity temperature variation in two sectors.

2.2 Instability Compensation

The beam appeared to become unstable when the cavity temperatures cycled to their minimum values; therefore, the cavity water supply temperatures were increased in an attempt to shift the HOMs out of resonance with the beam. Sector 37 water temperature was increased by 1.5°F and sector 40 was increased by 1°F. The CB instability was thereby essentially suppressed on following stores (Fig. 6).

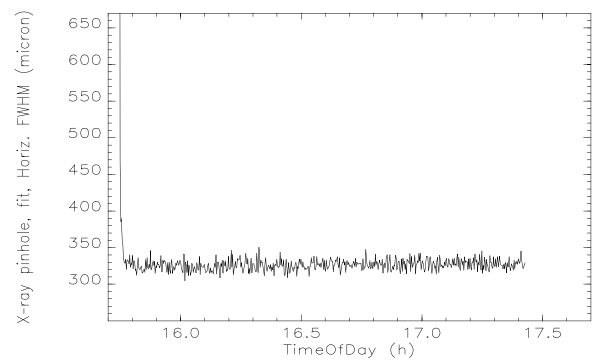

Figure 6: Constant horizontal beam size, 100-mA store, after CB instability compensation.

3 DRIVING RF CAVITY HOM

In the coupled-bunch instability theory, a resonance condition exists between one or more HOM frequencies, f_{HOM}, and the f_{rf} harmonics, p, the f_{rev} harmonics, n, the f_s harmonics, m, and the coherent mode frequencies, Ω_m [2]:

$$f_{HOM} = pf_{rf} \pm nf_{rev} \pm mf_s \pm \Omega_m \approx pf_{rf} \pm nf_{rev}.$$

Because f_s and Ω_m are much smaller than f_{rev}, the expression is simplified as shown on the RHS.

The CB mode envelope in Fig. 2 is centered around 154 MHz from either rf harmonic; therefore, the CB mode is near $\pm 154/f_{rf} \times h = \pm 570$. Plugging this value of n into the expression above for different values of p gives the candidate frequencies listed in Table 2. The one frequency closest to an rf cavity HOM is 1210 MHz [3]. This is the TM_{013} monopole mode, which has a relatively large temperature response consistent with the results of section 2.2.

Table 2: Possible Driving Frequencies of CB Mode

p	n=570	n=1296-570=726
5	1914 MHz	1958 MHz
4	1562	1606
3	1210	1254
2	858	902
1	506	550

Measurements of the beam-excited rf cavity HOM spectra for different bunch patterns also suggest that the TM_{013} mode is involved in the observed CB instability. The spectra were measured using E-type probes in the rf cavities. High-resolution measurements centered on a rotation harmonic revealed a large upper synchrotron sideband, excited when the beam was unstable (Fig. 7).

The excited HOMs were also measured over a wide frequency range with a resolution bandwidth $\geq f_{rev}$ for stable and unstable beam conditions. These are shown compared to the beam CB spectrum in Fig. 8. The lines marked show increased excitation in one cavity when the beam is unstable. The leftmost marked line is the 1210-MHz mode. The others are possibly aliased lines; the cavity probe detects true HOMs as well as beam power. It should be noted that the coupling of the cavity E-probe varies from mode to mode, and therefore, additional HOMs may be excited by the unstable beam but not revealed by the probe.

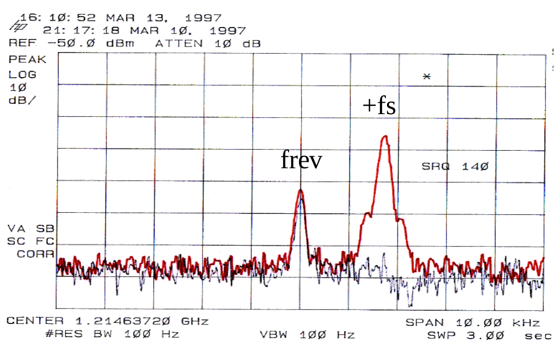

Figure 7: Rf cavity signals centered on 1214.64 MHz.

4 DISCUSSION

Detailed measurements for the symmetric 4×12 bunch fill pattern were presented thus far to demonstrate the character of the CB instability in the storage ring. A number of observations follow, based on studies of about a dozen different patterns. For each unstable pattern, the same CB mode was observed in the beam, implying the same HOM is responsible. Suppressing the instability by raising the cavity temperatures suggests this is truly driven by a long-range, high-Q impedance. The instability threshold was near 100 mA; it did not appear for, say 25 mA in a single train. If short-range wakefields are involved, they are not the dominant effect. However, transient beam-loading cannot be neglected in a partially-filled ring [4].

The CB instability seemed to depend on the bucket interval between the first bunches of each train. The bucket interval for the symmetric, unstable patterns was a multiple of 108. For the observed CB mode, this spacing ensures that synchrotron oscillations of the first bunches of each train are in phase. When the symmetry was broken using the same M×N bunches but with a bucket interval of 250 instead of 324, the instability was not observed. A curious sensitivity to the length of the train was seen. Increasing the train length by only one additional bunch could stabilize or destabilize the beam. Finally, the instability is nearly always in a saturated state, thus the growth rate is difficult to determine. The driving impedance based on a minimum growth rate of τ_D (synchrotron damping) is overestimated for the partially-filled ring.

A detailed spectral analysis of the bunch train and cavity response is planned to address some of these effects. A modification to an existing passive HOM damper design is also planned to increase coupling to the TM_{013} mode [5].

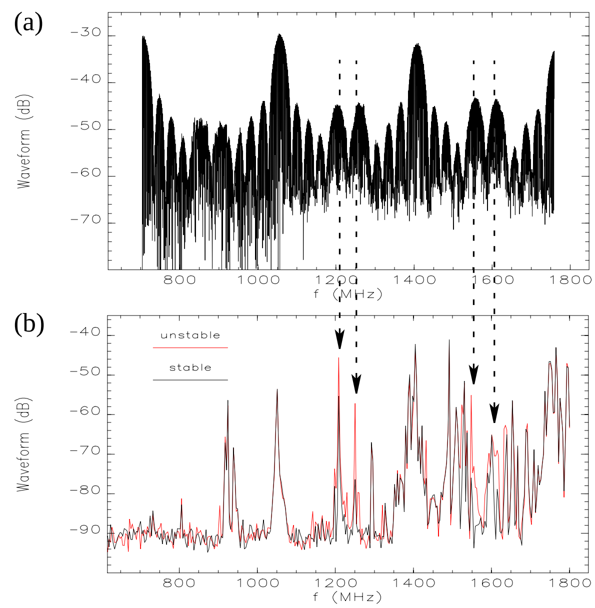

Figure 8: (a) Unstable beam CB spectrum, 4×12 bunch pattern vs. (b) excited HOM spectrum in rf cavity.

5 ACKNOWLEDGMENTS

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