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LONGITUDINAL MULTIBUNCH INSTABILITIES IN THE ADVANCED PHOTON SOURCE STORAGE RING

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Abstract

A longitudinal coupled-bunch (CB) instability was encountered in the 7-GeV Advanced Photon Source (APS) positron storage ring whose threshold depends on the bunch fill pattern in a nontrivial way. The beam spectrum exhibited a coupled-bunch signature, which could be reproduced by an analytical model. The beam fluctuations were found to be correlated with the rf cavity temperatures, consistent with the measured temperature dependence of the higher-order mode (HOM) frequencies. Fast beam loss due to a multibunch effect was observed with other patterns of very long bunch trains. The nature of these instabilities has not yet been characterized. Multibunch instabilities had not been observed previously with electrons, although such patterns of long bunch trains were not studied systematically in this case.

1 INTRODUCTION

Multibunch instabilities were first encountered with positrons in the APS storage ring (SR) when filling long bunch trains for beam position monitor (BPM) triggering. A variety of bunch fill patterns have been studied in the process of optimizing BPM performance in orbit control and establishing standard patterns for user operations. Typically, between 40 and 200 bunches are stored out of a possible 1296. It was discovered that for some fill patterns, a longitudinal coupled-bunch (CB) instability was observed with a threshold current ≤ 100 mA. The likely driving rf cavity higher-order mode (HOM) has been identified. Multibunch collective effects leading to fast beam loss were observed for other fill patterns as well. The nature of these effects has not yet been fully characterized. Selected parameters for the SR are found in Table 1. The nominal stored current is 100 mA, with a design goal of 300 mA.

The HOM-driven CB instability does not limit SR operation at 100 mA. The unstable patterns are easily avoided, and any coupled-bunch motion can be stabilized by changing the cavity water temperatures. The unstable beam oscillation amplitude is self-limiting, and there is minimum beam loss up to the nominal current.

Table 1: Nominal APS Storage Ring Parameters

Circumference	1104	m
Energy	7.0	GeV
Nominal current	100	mA
Harmonic number, h	1296	
rf frequency	351.927	MHz
rf gap voltage	9.4	MV
Synchrotron frequency	1.9	kHz
Energy loss /turn (dipole magnets)	5.45	MeV
Energy loss /turn (40 IDs)	1.25	MeV
Damping time, longitudinal	4.73	ms
Nominal bunch length, rms	40	ps
Momentum compaction	2.28×10^{-4}	
Horizontal, vertical tune	35.2, 14.3	
Beam size at ID, rms (H, V)	190, 50	μm
Natural emittance (measured)	7.6 ± 0.8	nm-rad
Average vacuum (100 mA, nominal fill)	0.8	nTorr

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The experimental observations and analysis are discussed below. The standard, stable user fill patterns are described first. Following is a discussion of the fill-pattern dependent CB instability. Multibunch instabilities observed with other fill patterns are discussed last.

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2 STANDARD USER FILL PATTERNS

Before studying the unstable bunch fill patterns, it is instructive to review the stable patterns adopted for SR user operations. An inverse chronology of standard user fill patterns is given in Table 2, with the most recent pattern at the top. The particular fill pattern is denoted as M×N, where M is the number of groups, or trains, of N bunches in a train. A bunch train specifically means adjacent rf buckets are filled. The interval between the first bunches in each group is given in the second column in the table. For example, 12 triplets spaced at intervals of 108 buckets span all 1296 buckets. Seventeen triplets spaced by 36 buckets span only 612 buckets. A charge of 2.3×10^{10} electrons gives 1 mA.

The earlier fill patterns consisted of several trains, each less than nine bunches, placed symmetrically about the ring. The SR was sparsely filled during initial operation with electrons, and systematic studies to search for multibunch instabilities were not performed. Later patterns with positrons are asymmetric and include a 6- or 12-bunch "BPM group," with 10 or 25 mA, respectively, leaving a gap of between 0.5 and 1 μs for triggering. The remaining charge is stored in the trailing groups of singlets, doublets, or triplets. All the fill patterns in Table 2 are stable; a single 25-mA, 12-bunch train did not give rise to CB instabilities, nor did 200 bunches spaced at two-bucket intervals.

Table 2: Chronology of Standard, Stable User SR Bunch Fill Patterns

M×N (groups × # in train)	bucket interval of groups	electrons or positrons	symmetric?	stable current (mA)	bunch charge (10^{10})
6 + 17×3 [a]	36	e+	n	102	4.1
6 + 200×1 [b]	2	e+	n	102	1.0
12 + 15×2	72	e+	n	102	5.5
12 + 30×1	36	e+	n	102	5.5
6×9	216	e-	y	100	4.3
12×3	108	e-/e+	y	100	4.8
12×6	108	e-/e+	y	100	3.2
36, 48×1	36, 27	e-	y	100	6.4, 4.8

a. 6- or 12-bunch train is "BPM group"; ×3 = triplets, ×2 = doublets, etc.

b. 90 mA in 200 bunches, every other bucket filled

3 FILL-PATTERN DEPENDENT COUPLED-BUNCH INSTABILITY

The physics of coupled-bunch instabilities driven by long-range wakefields such as those produced in the excitation by the beam of high-Q HOMs in the rf accelerating cavities is well understood in uniformly-filled rings [1]. The bunch oscillations occur at harmonics of the synchrotron frequency, modulating specific rotation harmonics in the frequency spectrum of the beam current. There are ± h/2 possible coupled-bunch modes, n, in which the phase of the ν^{th} bunch is $2\pi n\nu/h$. In a partially-filled ring, the interbunch phase is preserved, but the CB spectrum becomes degenerate. The standard Sacherer formula overestimates the instability threshold and growth rates for such a ring.

Dependence of a CB instability on bunch fill pattern has recently been reported at several machines in addition to the APS: e.g., ESRF [2], NSLS [3], and CESR [4]. Various analyses and modeling efforts are underway to characterize this effect. In the case of ESRF, Naumann and Jacob have shown that Landau damping introduced by beam-loading-induced synchrotron frequency spread can account for the deviation of the instability threshold from the Sacherer formula [2]. Probability estimates for coupled-bunch instabilities were performed for the SR [5] based on a normal mode analysis method developed by Thompson and Ruth [6] for the more general case of multiple bunch trains, not necessarily symmetrically spaced. The SR analysis used a symmetric, sparsely-filled pattern of single bunches to compute HOM deQing requirements at 300 mA. To fully characterize the pattern-dependence of CB instabilities observed at the SR with long bunch trains, a combination of beam loading and generalized normal mode analysis is likely needed. The results of such modeling will be reported in the future. This paper is focused on the experimental observations.

3.1 Observations

The CB instability was first encountered with a symmetric 4×12 bunch pattern, illustrated in Fig. 1. 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. Details of this correlation are reported in Refs. [7] and [8]. The SR beam spectrum was observed using the raw signal from a non-zero dispersion BPM button, and the transverse beam size and centroid motions were observed using a bending magnet x-ray pinhole diagnostic signal. The pinhole signal is processed in real time at a rate less than the synchrotron frequency, f_s; therefore, synchrotron oscillations result in an effective horizontal beam size growth.

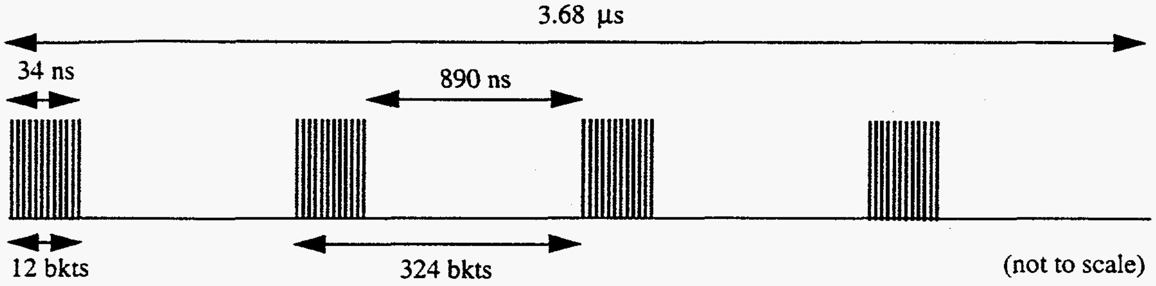

Figure 1: 4×12 bunch fill pattern schematic in time domain.

Beam spectra for the 4×12 bunch pattern are shown in Figs. 2 and 3, 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 the Fourier transform of a model 12-bunch train matches the amplitude-modulation envelope of the rotation harmonics of the data in Fig. 2. The number of peaks in the envelope correspond to number of bunches in a train, and the spacing of the revolution harmonics under envelope (not resolved in the measurements) gives the number of trains. The unstable beam spectrum in Fig. 3 exhibits a coupled-bunch signature. When an interbunch phase advance corresponding to a CB mode of n=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.

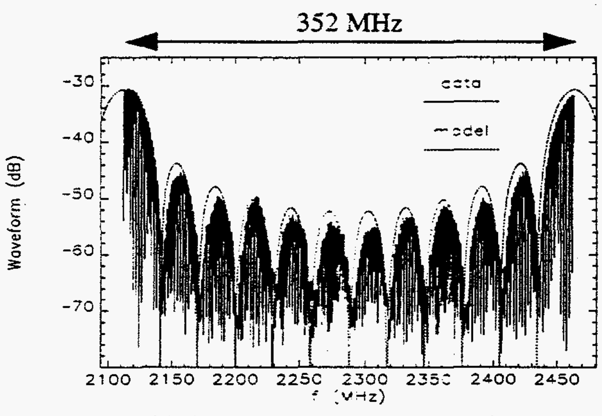

Figure 2: Stable beam spectrum, 4×12 bunch pattern.

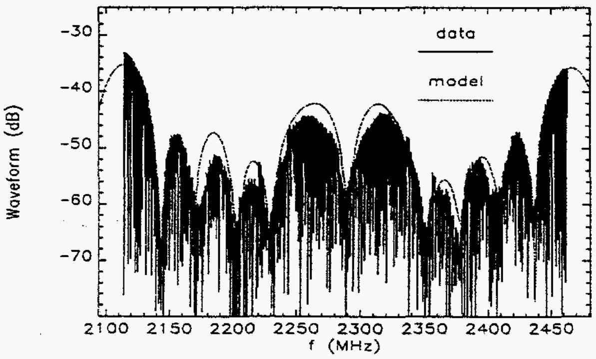

Figure 3: Unstable beam spectrum, 4×12 bunch pattern.

A curious sensitivity to the length of the bunch train was seen. Increasing the train length by only one additional bunch could stabilize or destabilize the beam. For unstable fill patterns, the lifetime was markedly poor, and 100 mA typically could be reached only with difficulty due to beam losses during injection. This is shown in Figure 4. The first fill was marginally stable, with some CB motion but with nominal lifetime. A scraper was used to extract beam before the 13th bunch was filled to the same current. Repeated attempts to fill the 13th bunch are shown in the center of the figure. The threshold for CB instability for the 4×13 pattern was decreased relative to 4×12, and the maximum oscillation amplitude was 5 dB higher. Finally, after the beam current decayed naturally, the 14th bunch was filled. This pattern was entirely stable (the beam was intentionally dumped at this point). Landau damping due to beam-loading-induced frequency spread implies that longer bunch trains would always be more stable. This is evidently not the case here.

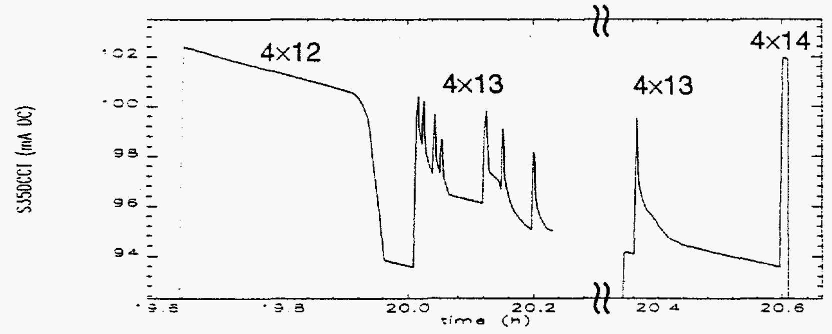

Figure 4: CB instability and beam lifetime.

- More than a dozen different fill patterns were studied, as listed in Table 3. The instability threshold is loosely defined as the current at which the coupled-bunch mode lines appear. For each of these unstable patterns, the same CB mode was observed in the beam, implying the same HOM is responsible. The instability depends more on the train length and symmetry of placement in the ring than on the single-bunch current. The unstable bunch train lengths were 11 or greater; the 6×9 pattern was stable (see Table 1). The bucket interval of groups 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.

Table 3: CB Instability for SR Bunch Fill Patterns Studied

M×N (groups × # in train)	bucket interval of groups	electrons or positrons	symmetric?	stable or unstable	instab thresh (mA)	stable current (mA)	bunch charge (10^{10})
4×11	324	e+	y	U	93		4.7
4×12	324	e+	y	M [a]	99 - 101		4.8
	250	e+	n	S		101	
4×13	324	e+	y	M [b]	93 - 99		4.2
	250	e+	n	S		102	4.4
4×14	324	e+	y	S		101	4.1
	250	e+	n	S		101	
4×15	324	e+	y	S		101	3.8
4×16	324	e+	y	S		100	3.6
3×13	432	e+	y	U	90		5.3
3×14	432	e+	y	U	99		5.5
3×27	108	e+	n	U	> 80		2.3
2×27	216	e+	n	U	~ 100		4.3

a. marginally stable
b. more unstable than 4×12

3.2 Driving Rf Cavity HOM

In a uniformly-filled ring, the CB spectrum is periodic in $f_{rf}/2$. When the fill pattern is nonuniform, the CB spectrum is highly degenerate. One result is an uncertainty in the CB mode number, which introduces some difficulty in identifying the driving HOM. 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. 5 for the unstable 4×12 fill pattern.

The CB mode envelope in Fig. 3 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 Sacherer's formula [9] gives the candidate frequencies listed in Table 4, where p is the rf harmonic. The one frequency closest to an rf cavity HOM is 1210 MHz [10]. This is the TM_{013} monopole mode, which has a relatively large measured temperature response [8]. The HOMs are deliberately frequency-staggered by varying the individual cavity lengths; however, temperature variations can shift them into coincidence.

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. 6). The excited HOMs were also measured over a wide frequency range with a resolution bandwidth $\geq f_{rev}$ for stable and unstable beam conditions. Figure 7 shows the spectrum in one cavity compared to the beam CB spectrum over three rf frequency spans. The lines marked show increased excitation when the beam is unstable. The leftmost marked line is the 1210-MHz mode. The others are likely to be 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.

The beam appeared to become unstable when selected 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. The water temperature for the four cavities each in sectors 37 and 40 was increased by 1.5°F and 1°F, respectively. The CB instability was thereby essentially suppressed. Suppressing the instability by raising the cavity temperatures strongly 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. Finally, the instability is nearly always in a saturated state, thus the growth rate is difficult to determine.

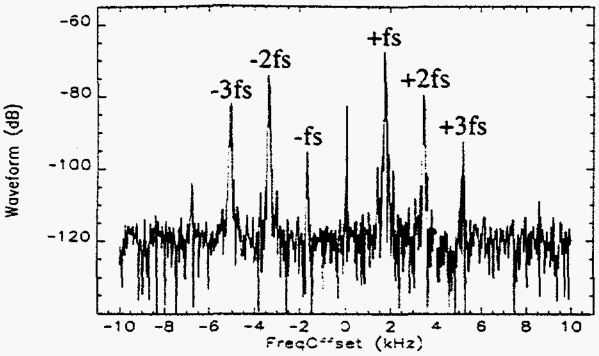

Figure 5: Unstable beam spectrum, centered at $7f_{rf} + f_{rev}$.

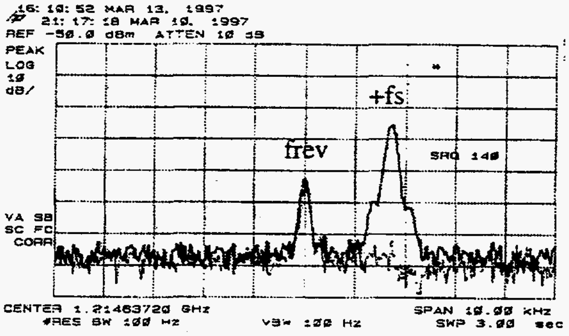

Figure 6: Rf cavity signals centered on 1214.64 MHz.

Table 4: 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

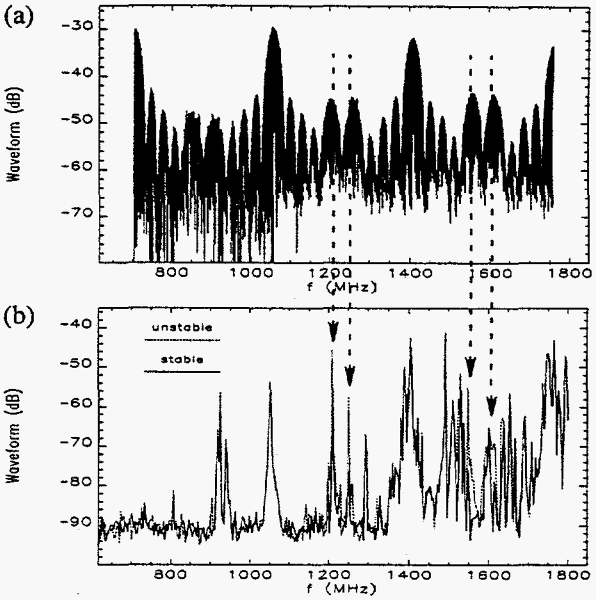

Figure 7: (a) Unstable beam CB spectrum, 4×12 bunch pattern vs. (b) excited HOM spectrum in rf cavity.

4 OTHER FILL PATTERNS

Multibunch instabilities leading to fast beam loss have been observed in a number of other fill patterns of very long bunch trains. A list of these patterns is found in Table 5. The beam spectra have not been studied in depth for most of these patterns, thus the exact nature of these instabilities has not yet been characterized. The unstable symmetric fills are likely to exhibit coupled-bunch modes; the growth rates are of the order of the damping rate, and there is little beam loss. Further experiments are required to determine the cause of beam loss for the very long single-bunch trains. One should note the last entry in the table: 164 mA was reached with electrons in 120-140 bunches without multibunch instabilities.

Table 5: Other SR Bunch Fill Patterns

M×N (groups × # in train)	bucket interval of groups	electrons or positrons	symmetric?	stable or unstable	instab thresh (mA)	stable current (mA)	bunch charge (10^{10})
1296 × 1	1	e+	y	U	93		0.16
648 × 1	2	e+	y	U	93		0.3
1 × 32, 200	1	e+	n	U	> 60		4.3, 0.7
1 × 729	1	e+	n	S		50	0.2
1 × 177-378	3	e+	n	S		50	0.3-0.6
2×27	216	e+	n	U	~ 100		4.3
12×1	108	e-/e+	y	U	> 83		15.9
120 - 140 [a]	?	e-	y	S		164	2.7-3.1

[a] total # bunches; bunch pattern not recorded

- An interesting observation was made with every bucket or every other bucket filled. Figure 8 shows the unstable spectrum for every bucket filled when the current was above 93 mA; only the rf harmonics were present below this current. Zooming in on the revolution harmonics within the peaks of the spectrum (not shown) reveals strong synchrotron sidebands, indicating longitudinal oscillations. It should be noted that the bunch intensities varied by about 50%, which may explain some of the spectral structure. The driving HOM has not been identified, but it is not the same mode as for the patterns in Table 3. Figure 9 shows a comparison just above (102 mA) and just below (85 mA) the instability threshold of the spectral power at all harmonics for every other bucket filled. Two unstable mode lines appear for every mode line in Fig. 8. Figure 10 shows the response at the betatron tunes, which are measured by driving the beam through a stripline with a network analyzer. The vertical tune splits in two and shows strong synchrotron sidebands when the longitudinal oscillation amplitude is large. The horizontal tune is less perturbed.

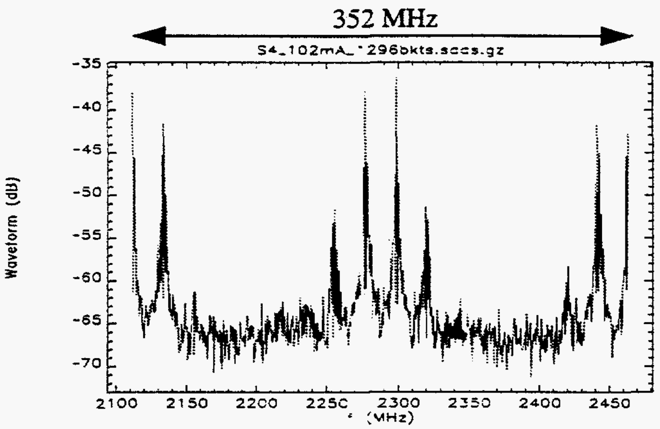

Figure 8: Unstable spectrum, every bucket filled.

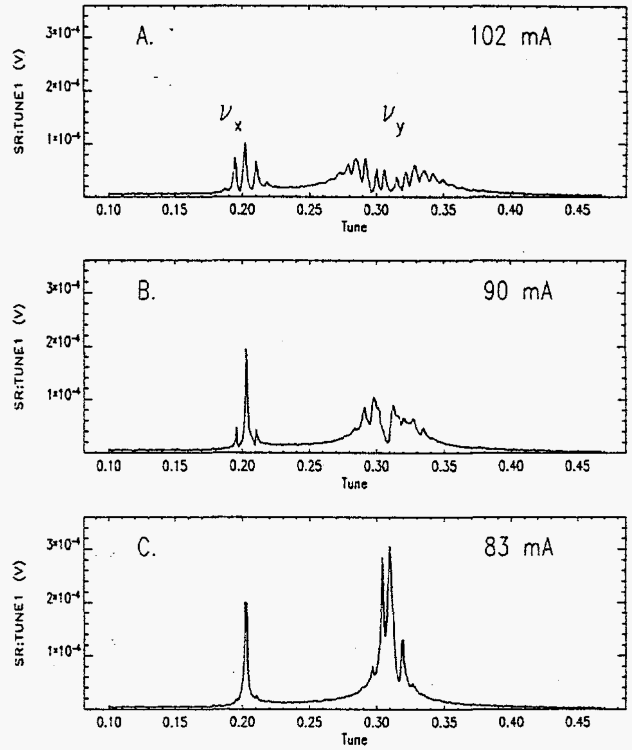

Figure 10: Driven response at betatron tunes, every other bucket filled.

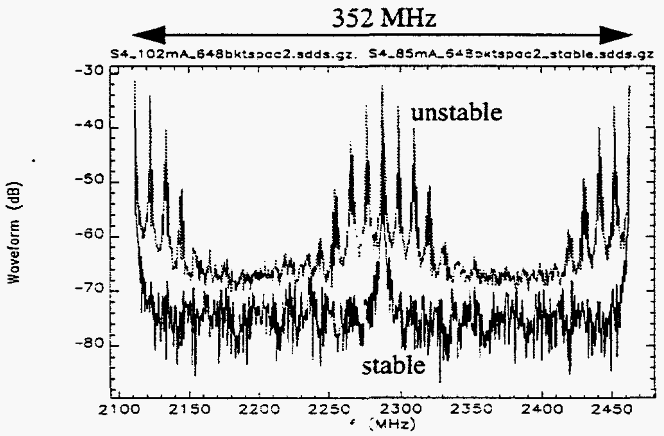

Figure 9: Comparison of stable and unstable spectra, every other bucket filled. The instability threshold is ~93 mA.

5 DISCUSSION

An existing model based on the normal mode method of Thompson and Ruth will be expanded to study the stability of multiple bunch trains including beam loading effects. A comprehensive fill-pattern dependent CB mode model is desired for predicting the stability of future user-desired fill patterns. Further experiments are planned to characterize the instability of long bunch trains to determine the growth rates and thresholds in terms of train length vs. current. Measurements of the cavity response are required before HOM-driven CB instabilities can be ruled out. Additional diagnostics are planned [11] that will enable the correlation of the instabilities of long bunch trains with the electron cloud density.

6 ACKNOWLEDGMENTS

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