Measurements of Collective Effects in the ALS*

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Abstract

The Advanced Light Source (ALS) is a newly commissioned 1.5 GeV third generation synchrotron radiation facility. We present a summary of measurements of single and multibunch collective effects in the ALS storage ring and correlations with the expected impedance. Longitudinal and transverse coupled-bunch (CB) oscillations are characterized using measurements of beam spectrum, transverse beam size in dispersive regions, and undulator spectral width. Single bunch transverse head-tail damping rate and frequency shift are used to develop a model of the transverse broadband impedance. To date, storage ring performance is limited by longitudinal coupled–bunch oscillations. No deleterious single-bunch effects up to 20 mA have been observed.

INTRODUCTION

Collective effects in a storage ring describe the interaction of the beam with the surrounding vacuum chamber via the electromagnetic field of the beam. We are most concerned with the interactions which destabilize beam oscillations, distort the beam size and distribution, and hence generally degrade the quality of synchrotron radiation from the beam.

We present in this paper a summary of the measurements of collective effects to date. The results are divided into the categories of coupled–bunch and single bunch effects. The former describes the effects of narrowband impedances and the latter the broadband impedance of the ring. Because of the immediacy of the problem, the concentration is on coupled–bunch effects, which have been observed and currently provide a limitation to performance of the light source.

COUPLED–BUNCH MEASUREMENTS

Coupled–bunch (CB) oscillations in the longitudinal plane are expected to be driven by high–Q monopole HOMs of the two RF cavities and in the transverse planes the dipole HOMs and the resistive wall impedance. Measurements and calculations of the driving impedances as well as the resulting CB growth rates are described elsewhere[1, 2].

During normal operation the storage ring filling pattern has every RF bucket filled roughly equally with a 0-10% gap for ion clearing to a total current of ~400 mA. Spontaneous longitudinal oscillations occur at 5-20 mA total beam current without much dependence on the fill pattern. However, the oscillations saturate at a level which then slowly increases with current. Oscillation amplitudes have been measured at 5–10σ. They do not appear to cause any beam loss but rather improve the lifetime, probably from the dilution of the beam density.

Parameter	Description	Value
E	Beam energy	1.5 GeV
C	Circumference	196.8 m
f_{rf}	RF Freq.	499.654 MHz
σ_ϵ	RMS $\delta E/E$	7.1e-4
h	Harmonic Number	328
I_0	Design beam current	0.4 A
α	momentum compaction	1.594e-3
Q_s	Synchrotron tune	0.006
σ_ℓ	RMS bunch length	6 mm
$Q_{x,y}$	Betatron tunes (x,y)	14.28, 8.18

Table 1: Selected ALS parameters.

We diagnosed the instabilities by passively observing the beam spectrum using a BPM sum signal. In order to simplify identification of the coupled oscillation modes and correlate them with the driving impedance, we used fill patterns of equally spaced, equally charged bunches. Observed on a spectrum analyzer, the beam current spectrum has frequency components at multiples of the bunch harmonic frequency, Nf_0, and the oscillations of individual CB modes appear as phase modulation (PM) sidebands about the bunch harmonics. The amplitude of phase modulation of CB mode ℓ can be determined from the ratio of the first order sideband to the carrier. Note that all N CB modes can be measured in a frequency span of pNf_0 to $pNf_0 + \frac{Nf_0}{2}$.

In our measurements, the storage ring was filled in symmetric patterns of 82 and 328 bunches and the amplitudes of all longitudinal CB modes were measured as a function of current. Unavoidable variations in the charge of each bunch lead to small frequency components at revolution harmonics between bunch harmonics and were used as a measure of the uniformity of the fill pattern. We observed 1–5% variations in the bunch uniformity around the ring. The process of recording the sidebands of many revolution harmonics was automated by way of a MacIntosh computer equipped with a GPIB interface.

Shown in Figure 1 are some representative beam spectra measured at 20 and 95 mA showing the CB mode oscillations which appear as upper or lower sidebands of the revolution harmonics. The center peak in each spectrum is the residual revolution harmonic from the asymmetry in the bunch charges. The sidebands at f_s and $2f_s$ are first and second order PM sidebands. The amplitude of all CB

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*This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

modes for the 328 bunch configuration is shown in Figure 2a. The oscillation amplitudes are expressed in degrees of phase modulation at the RF frequency, 500 MHz.

The patterns observed in the amplitude of the CB modes can be interpreted by comparing them with the effective impedance, for a given bunch filling pattern evaluated using the measured parameters of the RF cavity HOMs. The real part of $\left[Z_{\|}\right]_{eff}$ for the 328 bunch case is shown in Figure 2b. The left axis is the effective impedance and the right axis the corresponding growth rate at 95 mA. The dotted line represents the effective impedance resulting in growth for CB modes corresponding to upper sidebands in the frequency range. The dashed line is the effective impedance resulting in growth for lower sidebands in the same frequency range. The aliased HOM's are labeled according to their resonant frequency as given in [2].

Comparing the effective impedance with the CB mode amplitudes for each filling pattern, we can correlate the beam spectrum with the measured impedance and positively identify the driving HOMs. At 95 mA, the strongest CB modes are driven by the high-Q TM-011 mode (f_r=808 MHz) and the next strongest CB modes by the HOMs at 2.3 and 2.8 GHz. Experiments changing the cavity temperature and tuner position show that the stability of the CB mode driven by the high-Q mode changes greatly with cavity conditions. Unfortunately, cavity conditions do not greatly affect the lower-Q HOMs. We see a similar correlation with the effective impedance in the 82 bunch case.

Preliminary results on the spectrum of light from an undulator also indicate large longitudinal, or energy, oscillations. Because the spectral width of the synchrotron radiation depends partly on the effective energy spread of the beam, significant widening of the higher harmonics of the undulator has been observed[3]. This has resulted in a marked decrease in the brightness in multibunch operation. Several passive techniques for curing the instabilities such as modulation of the RF voltage and partial filling of the ring have not yet been successful in reducing the oscillations.

Similar studies of the beam spectrum were performed in the two transverse planes. The pattern of CB modes indicates that the dominant driving impedance is the resistive wall. However, the motion does not reach amplitudes greater than ~50 microns. We believe the transverse stability is greatly increased by the relatively large amplitude longitudinal oscillations, probably via the chromaticity. We hope to make further studies when the longitudinal FB system is in place.

SINGLE BUNCH MEASUREMENTS

Single bunch instabilities are driven by wakefields which persist over the length of bunch. In the frequency domain, this is referred to as the broadband impedance. Because single bunch instabilities have not yet been a problem at ALS, we provide in this section only a cursory view of our measurements to date. For simplicity, the broadband impedance is assumed to be a Q=1 resonator with a cutoff frequency of f_r=2.8 GHz, the average cutoff of the vacuum chamber. Impedance measurements of ALS vacuum chamber components are described elsewhere[4].

We do not yet have a diagnostic bunch length measurement. However, we have attempted to probe the resistive part of the broadband impedance by measuring a shift in the synchronous phase angle vs. bunch current. No shift was measureable up to 12 mA with an accuracy of 1 degree. This yields an upper limit $|Z/n|_{\|,eff} < 0.2\ \Omega$. Efforts to extract the energy spread from the measurements of widths of undulator harmonics are underway. This may allow a measurement of the microwave instability threshold.

The standard technique for probing the transverse broadband impedance is to measure the single bunch betatron tune shift vs. bunch current and the head-tail damping rate vs. bunch current and chromaticity. The damping rates were measured using the transient from an injection bump. Unfortunately, we were not able to reliably produce measureable vertical transients. We measured tune shifts with current of $dQ_x/dI = -4.9\pm0.6\times10^{-5}$/mA and $dQ_y/dI = -2.0\pm0.15\times10^{-4}$/mA. The head-tail measurements yield $d(\tau_x^{-1})/dId\xi = 1.34 \pm 0.04$/msec-mA, where the chromaticity $\xi \equiv dQ/Q/dE/E$. This is consistent with a broadband impedance of 170 kΩ/m in the horizontal plane. There is no evidence of transverse mode coupling instability.

CONCLUSIONS

Beam instabilities have not limited the total current in the ALS storage ring up to ~470 mA. However, large longitudinal CB oscillations significantly degrade the quality of synchrotron light. CB feedback systems have been tested with the final versions operational within a year. No single bunch instabilities have been observed. Single bunch measurements indicate an effective longitudinal broadband impedance $|Z/n|_{\|,eff} < 0.2\ \Omega$.

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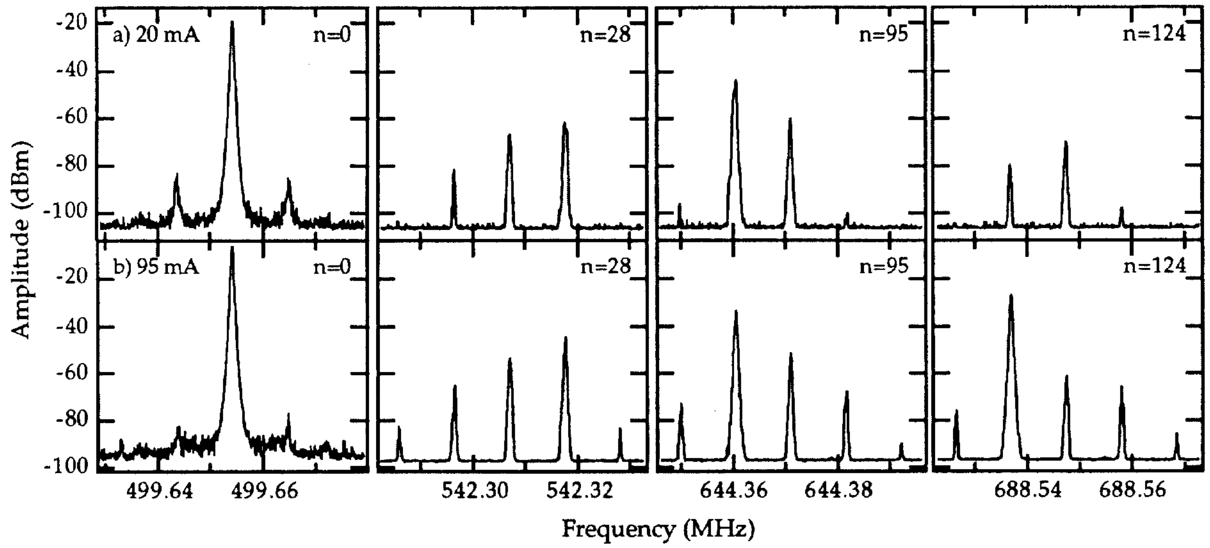

Figure 1: Raw frequency spectra of selected coupled bunch modes. The number of revolution harmonics from the RF frequency is indicated in each plot. The top row is at 20 mA and the bottom at 95 mA total current.

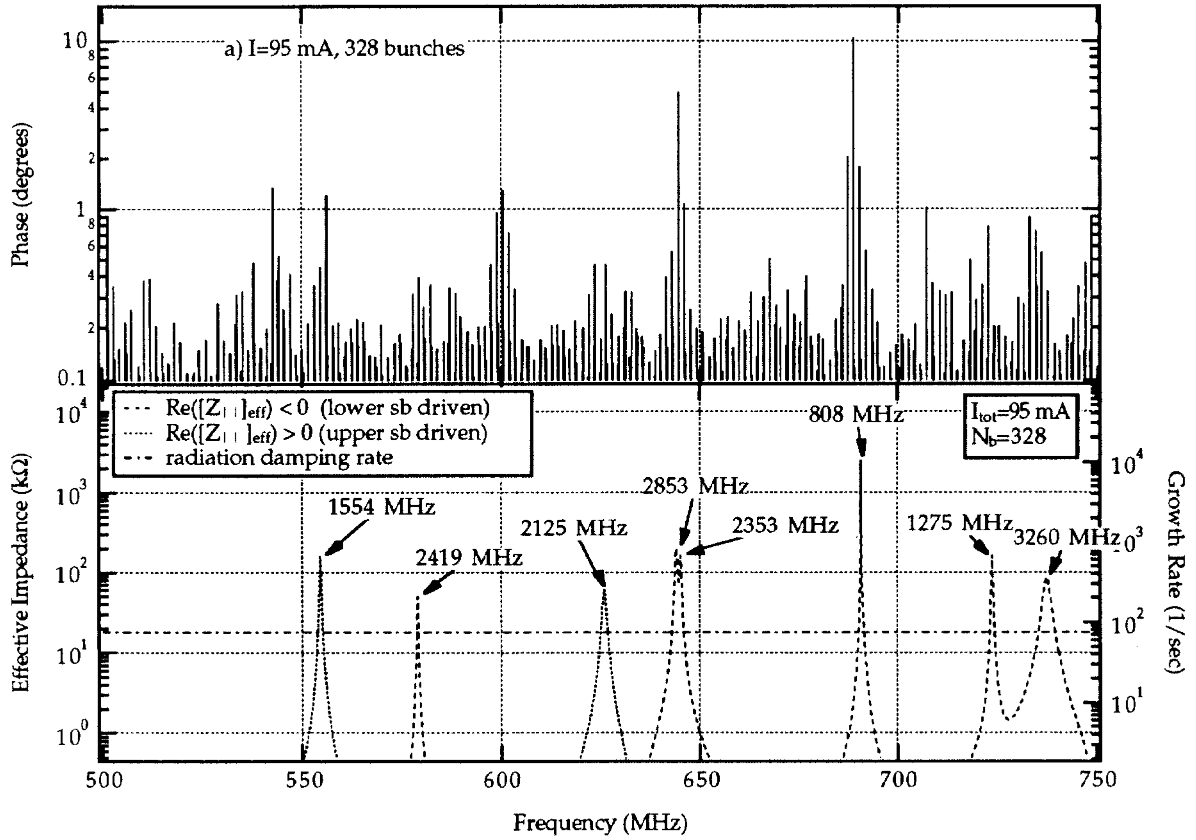

Figure 2: a) Measured spectrum of first-order longitudinal sidebands for 328 bunches in the frequency range 500-750 MHz at 95 mA. b) Real part of the RF cavity impedance aliased into the same frequency range. The corresponding growth rate for 95 mA is shown on the right axis.