Single Bunch Collective Effects in the ALS*

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Abstract

We present a summary of measurements of single bunch collective effects in the Advanced Light Source (ALS). These effects include bunch lengthening, energy spread increase, HOM loss measurements, head-tail damping rates, current dependent tune shifts, and transverse mode coupling instability threshold. The longitudinal measurements are consistent with a broadband impedance $|Z_{\|}/n|_{eff} = 0.22 \pm 0.07\ \Omega$ and transverse measurements indicate broadband impedances of $Z_{y,eff} = 155\ k\Omega/m$ and $Z_{x,eff} = 58\ k\Omega/m$.

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	Bunch current	1–2 mA
α	momentum compaction	1.594e-3
Q_s	Synchrotron tune	0.006
σ_ℓ	RMS natural bunch length	5-10 mm
$Q_{x,y}$	Betatron tunes (x,y)	14.28, 8.18

Table I
Nominal ALS parameters.

I. Introduction

The ALS is a 1.5-1.9 GeV electron storage ring optimized for producing high brightness synchrotron radiation. General parameters are given in Table I.

Collective effects in a storage ring describe the interaction of the beam with the surrounding vacuum chamber via the electromagnetic wakefields of the beam. Single bunch effects are generated by wakefields which persist over the length of bunch but generally decay before arrival of the next bunch. In the frequency domain, these wakefields are referred to as the broadband impedance. Bench impedance measurements of ALS vacuum chamber components have been conducted are described elsewhere[1], [2]. Other collective effects in the ALS are described elsewhere[3], [4].

Single bunch currents up to 70 mA have been stored in the ALS, despite onset of the mode coupling instability (MCI) threshold in the vertical plane at ~28-30 mA. The vacuum chamber in one of the undulator straight sections was modified in December 1994, reducing the full height from 18 to 10 mm. Following this modification, the single bunch current was limited to 28 mA, probably because the reduced vertical aperture no longer contained the beam at the onset of the vertical MCI.

II. Longitudinal Measurements

A. Bunch Length and Energy Spread

Changes in the natural bunch length can typically be attributed to a combination of potential well distortion and the microwave instability (MWI). The former yields an increase or decrease in the bunch length and the latter an increase in the energy spread with a corresponding increase in the bunch length. The measurements shown below indicate that bunch lengthening in the ALS is dominated by growth of the energy spread via the MWI.

We used a technique for estimating the bunch length from the broadband frequency spectrum of a single button BPM which was designed to have a broadband response. Although it is very difficult to make an absolute measurement of the bunch length or longitudinal bunch distribution using this technique because the detailed response of the pickup/cable is unknown, one can make good measurements of the relative change in bunch length assuming that the longitudinal distribution remains Gaussian and that the bunch length is known at some current. In this case, the ratio of the bunch spectra is given by

$$ratio = \frac{S_2(\omega)}{S_1(\omega)}\ \alpha\ e^{-\omega^2(\sigma_2^2-\sigma_1^2)} \tag{1}$$

where $S(\omega)$ is the signal as a function of frequency observed on the spectrum analyzer.

We assumed that the bunch length at low currents (<1 mA) was given by the natural bunch length and extracted the bunch length by fitting the ratio of the bunch spectra out to ~6-7 GHz. Recently, a fast photodiode has become available and is beginning to be used for bunch length measurements. It shows good agreement with the bunch spectrum technique. Results of bunch length measurements for E =1.52 GeV and Q_s =0.0075 are shown in Figure 1. Fitting the data to a power law yields

$$\sigma_l(cm) = (0.36 \pm 0.03) I_b(mA)^{(0.33\pm0.02)} \tag{2}$$

Changes in the energy spread were extracted from measurements of the transverse beam profile at a point of dispersion in the lattice. The transverse profile is measured from synchrotron light in the UV range illiminating a BGO crystal. A video image of the profile is fit to a Gaussian. The dispersion was measured at the source point and the beta functions at the source point were extrapolated from measured values at nearby quadrupoles. The energy spread data is shown in Figure 2. Although an increase in the energy spread vs. current is apparent, there is no clear threshold visible.

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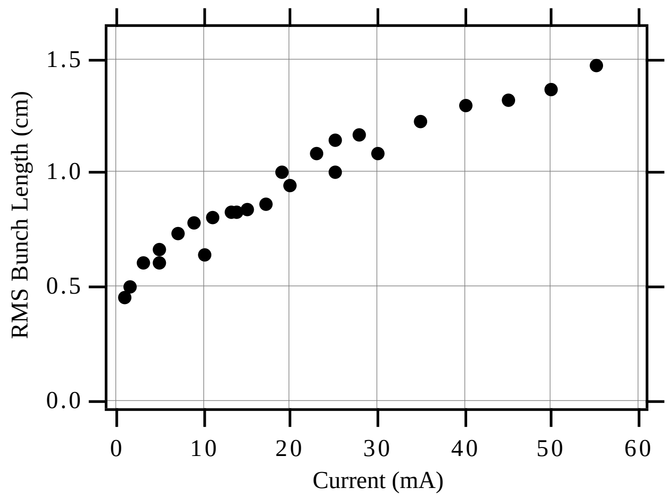

Figure. 1. Measured RMS bunch length vs current for E =1.52 GeV and Q_s =0.0075.

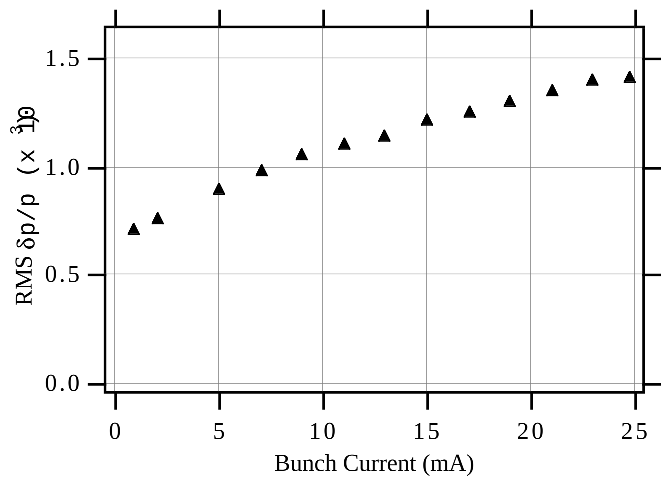

Figure. 2. Measured RMS energy spread vs current extracted from a transverse profile monitor.

The increase in the energy spread indicates that the bunch lengthening is at least partially due to the MWI. Assuming that the bunch length changes due to potential well distortion are negligible, the bunch length above threshold as a function of current is given by

$$\sigma_l^3 = \frac{\alpha R^3}{2\pi(E/e)Q_s^2}\left|\frac{Z_\parallel}{n}\right|_{eff} I_b \tag{3}$$

The power law dependence found from the bunch length data supports the assumption that the bunch lengthening results from the MWI. From this, we calculate $|Z_\parallel/n|_{eff} = 0.22 \pm 0.07$ Ω. The data from Figure 1 is shown on a log–log scale in Figure 3, along with the calculated bunch length dependence from Eq. 3 using the above value of $|Z_\parallel/n|_{eff}$, corresponding to a threshold value of 2.2 mA.

B. Higher Order Mode Loss

We have attempted to probe the resistive part of the broadband impedance by measuring a shift in the synchronous phase angle vs. bunch current. A cavity probe signal and a BPM sum signal were compared using a vector voltmeter. No shift was measureable up to 12 mA with an accuracy of 1 degree. This yields an upper limit on the loss parameter of $k < 2.2\ V/pC$. The loss parameter estimated from the bench measurements of vacuum chamber components is ∼3.8 V/pC. The beam measurement was made prior to the vacuum chamber modification.

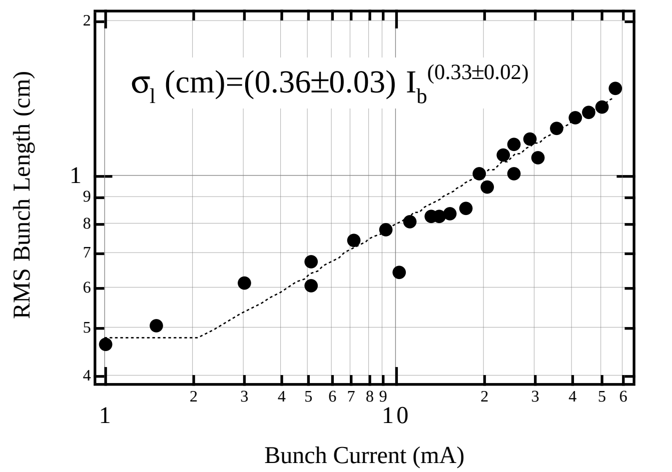

Figure. 3. Measured RMS bunch length vs current showing 1/3 power law dependence.

If the 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, the loss parameter yields a broadband impedance of $|Z/n|_{\parallel,eff} < 0.2$ Ω.

III. Transverse Measurements

The effective transverse broadband impedance is found from the measured single bunch betatron tune shift vs. bunch current and the head–tail damping rate vs. bunch current and chromaticity. We measured tunes using signals from standard button BPMs with the beam driven by stripline kickers. The damping rates were measured on a spectrum analyser in tuned receiver mode using the transient from an injection bump. Unfortunately, we were not able to reliably produce measureable vertical transients. We made an effort to minimize the influence of decoherence on the damping rates by measuring the transients at the lowest possible kick amplitude.

The tune shift measurements are summarized in Figure 4. They yield values of $dQ_x/dI = -4.9 \pm 0.6 \times 10^{-5}$/mA and $dQ_y/dI = -1.71 \pm 0.05 \times 10^{-4}$/mA. Following the modification of the vacuum chamber, the vertical tune shift vs. current increased to $dQ_y/dI = -2.29 \pm 0.05 \times 10^{-4}$/mA. (Measurements before and after the modification are referred to as pre– and post–VC in Figure 4.)

The transverse tune shift of the dipole mode vs. current is related to the effective impedance by[5]

$$\frac{dQ_\perp}{dI} = \frac{R}{4\sqrt{\pi}(E/e)\sigma_l}\beta_\perp Z_{\perp,eff} \tag{4}$$

where $\beta_\perp$ is the average β–function in the lattice. We find values of $Z_{y,eff} = 155 \pm 4\ k\Omega/m$ and $Z_{x,eff} = 58 \pm 7\ k\Omega/m$. We believe the ratio of vertical to horizontal impedance results from the combination of the beampipe aspect ratio and relative β functions.

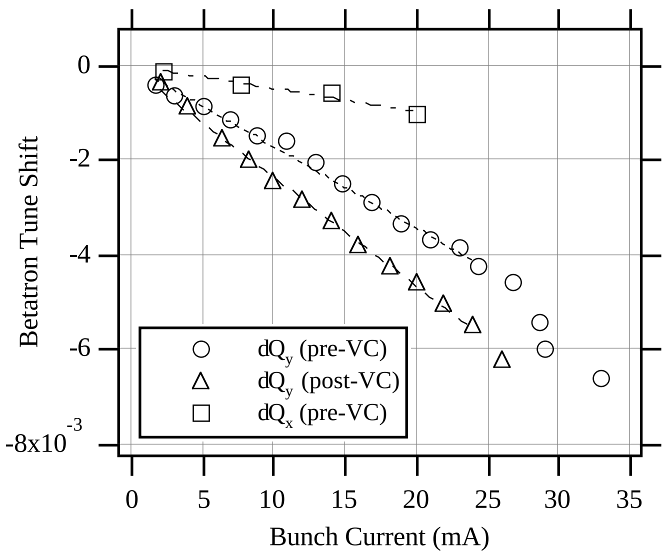

Figure. 4. Transverse tune shifts vs. current. A reduction of the vertical aperture from 18 to 10 mm in one of the straight sections resulted in a 33% increase in the effective vertical impedance.

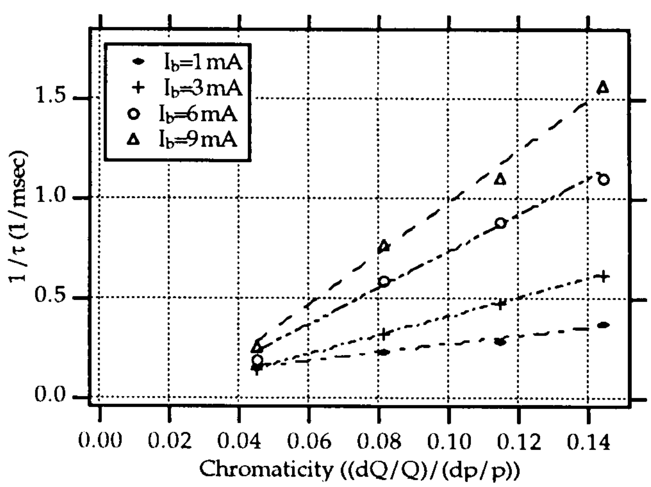

Figure. 5. Horizontal damping rates vs. chromaticity at several current levels.

The head–tail damping rate measurements are summarized in Figure 5. They yield a value $d(\tau_x^{-1})/dId\xi_x = 1.34 \pm 0.04$/msec-mA, where the chromaticity $\xi \equiv dQ/Q/dE/E$. The range of chromaticity values corresponds to a chromatic frequency shift of $f_\xi = \xi \frac{Q_\beta}{\alpha} f_0 = 2$ GHz. A cursory check did not indicate any dependence of the damping rate on bunch length. It is difficult to interpret these measurements in terms of an effective impedance without having a model of the frequency dependence of the actual impedance. We are awaiting further measurements under a wider variety of conditions before we do this analysis.

We observe a strong steady–state blowup in the vertical beam size at 25 mA which we associate with the threshold of the mode coupling instability, which agrees well with threshold calculated from the value of the vertical impedance found from the tune shift measurements. We cannot accumulate current higher than $\sim$28 mA. The threshold appears to be independent of chromaticity (positive values only) and proportional to changes in the synchrotron frequency. We are not able to observe any synchrotron sidebands of the betatron tunes before the instability threshold, typically associated with the first head–tail modes. Prior to the change in the vacuum chamber described above, the onset of the instability occurred at 28 mA but did not limit the beam current. The instability appears to be self-limiting, probably due to nonlinearities in the betatron motion, but at amplitudes which now exceed the vertical acceptance of the vacuum chamber. There also appears to be some hysteretic behavior in the blowup with beam current. After the onset of the instability, we must drop the current several milliamps below the threshold before it returns to its nominal size.

IV. Conclusions and Acknowledgements

Bunch length and energy spread measurements indicate the MWI as the mechanism for bunch lengthening although further measurements under different conditions are needed to check the scaling. The effects of narrowing vacuum chambers for decreasing gaps for insertion devices shows a measureable increase in the transverse impedance, effectively decreasing the maximum single bunch current. The authors would like to thank the ALS Operations Group for assisting in the measurements.

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