Measurements of Vacuum Chamber Impedance Effects on the Stored Beam at CESR*

M. Billing, Z. Greenwald, W. Hartung, W. R. Lou, M. Pisharody, J. Rogers, D. Sagan, J. Sikora
Laboratory of Nuclear Studies, Cornell University, Ithaca, NY 14853 USA

Within the last year CESR (Cornell Electron Storage Ring) has changed its mode of operation from 7 nearly equally spaced bunches in the two counter-rotating beams to 9 trains of 2 bunches in each of the beams as the next step in the upgrade of the facility toward higher beam currents and increased luminosity. The upgrade program has included work to understand and document the transverse stability of a single beam composed of trains of bunches. Initial results from this work will be reported here.

EIGEN MODES OF OSCILLATION FOR TRAINS OF BUNCHES

One of the most common methods for studying single beam collective effects consists of observing the change of the tune and of the damping rate for each of the eigen modes of oscillation of the beam as a function of the beam current. To make these measurements the eigen modes for trains of bunches and the eigen mode frequencies must be known. Although for brevity the following arguments will treat transverse dipole modes of oscillation, these arguments can be trivially generalized to higher transverse head-tail modes as well as to longitudinal modes of oscillation.

Following the formulation by Siemann[1], we may describe the betatron motion of a single bunch of particles driven by a sinusoidal excitation from a kicker as observed at a single beam position monitor (BPM) in the ring. On time scales much longer than the bunch length, the position signal from the BPM, d(t), can be represented as a complex phasor proportional to a sequence of delta-functions spaced at the revolution period T and modulated by the average position of the bunch times its current,

$$d(t) = x_0\, Q_b\, e^{j\omega_\beta t} \sum_{n=-\infty}^{\infty} \delta(t + nT)$$

where x_0 is the betatron oscillation amplitude at the angular frequency ω_β and Q_b is the charge in the bunch. The frequency spectrum of this dipole moment $d(\omega)$ is calculated by Fourier transformation to be

$$d(\omega) = x_0\, Q_b \sum_{n=-\infty}^{\infty} e^{\,j\, nT(\omega_\beta-\omega)} = x_0\, Q_b\, \omega_r \sum_{n=-\infty}^{\infty} \delta(\omega - \{\omega_\beta + n\omega_r\})$$

where $\omega_r = 2\pi / T$. This is a line spectrum with the lines occurring at the upper betatron sidebands of the rotation harmonics. When this signal is connected to a spectrum analyzer, negative frequencies are not observed directly but are reflected about zero into the positive frequency domain causing the negative frequency part of the spectrum to occur at the lower betatron sidebands of the rotation harmonics.

For the case of N_t trains of N_b bunches having a uniform spacing in time of T/N_t between the lead bunches of subsequent trains and a spacing of T_{bb} between the bunches within each train, the time domain signal will be the sum of dipole moments for each of the bunches giving us N_t times N_b sets of these delta-function sequences. The eigen modes of the betatron oscillations for this ensemble of bunches (charge Q_b per bunch) will be occur as stationary temporal patterns of displacements having the same maximum for each bunch in the beam. A stationary pattern of displacements means that each eigen mode must excite the bunches in an oscillation pattern that, if on one given turn the kicker's excitation was in phase with one of the bunches in the ensemble, a change of this excitation to be in phase with some other bunch would simply translate the pattern; this implies the displacements must satisfy periodic boundary conditions. The lowest eigen frequency of each eigen mode must then have a constant phase advance between lead bunches in adjacent trains of $2\pi\,(L/N_t)$ where $L = 0,1,...,N_t-1$ and a constant phase advance between bunches within the train of $2\pi\,(K/N_b)$ where $K = 0,1,...,N_b-1$. Thus the dipole moment of the ensemble of bunches, $d_{N_t,N_b}(L,K,t)$, driven at the lowest eigen frequency specified by mode parameters (L,K) is

$$d_{N_t,N_b}(L,K,t) = x_0\, Q_b \sum_{l_t=0}^{N_t-1} \sum_{k_b=0}^{N_b-1} \delta\left(t + \frac{l_t}{N_t}T + k_b T_{bb}\right) * \exp\left[j\omega_\beta\left(\frac{l_t}{N_t}T + k_b T_{bb}\right) + 2\pi j\,\frac{l_t\, L}{N_t} + 2\pi j\,\frac{k_b\, K}{N_b}\right]$$

where the last two terms in the exponential arise from the phase advances from train to train and from bunch to bunch within each train. The Fourier transform of $d_{N_t,N_b}(L,K,t)$ is

$$d_{N_t,N_b}(L,K,\omega) = S(\omega_\beta,L)\;\; I(\omega,K)$$

In this form $S(\omega_\beta,L)$ selects the spectral lines which are associated with the mode parameter L and these identify what we will call "train modes" of oscillation since there is a phase advance of $2\pi\,(L/N_t)$ from train to train. In this equation $I(\omega,K)$ is the envelope function for the "bunch modes" of oscillation which have phase advances of $2\pi\,(K/N_b)$ from bunch to bunch within each train. $S(\omega_\beta,L)$ and $I(\omega,K)$ are

$$S(\omega_\beta,L) = x_0\, Q_b\, \omega_r\, N_t \sum_{n=-\infty}^{\infty} \delta(\omega - \omega_\beta - \{nN_t + L\}\,\omega_r)$$

$$I(\omega,k) = \frac{\sin\frac{1}{2}\left[(\omega - \omega_\beta)N_b T_{bb} - 2\pi K\right]}{\sin\frac{1}{2}\left\{(\omega - \omega_\beta)T_{bb} - 2\pi\,\dfrac{K}{N_b}\right\}} * \exp\left\{-\frac{j}{2}\left[(\omega - \omega_\beta)(N_b-1)\,T_{bb} - 2\pi\,\frac{K(N_b-1)}{N_b}\right]\right\}$$

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Notice for a given mode L that $S(\omega_\beta,L)$ selects every N_t-th spectral line to associate with this mode while the N_t-1 intervening lines correspond to the other train modes. The form of $I(\omega,K)$ gives an interference pattern, whose first global maximum occurs at $\omega = 2\pi\ K/(N_b\ T_{bb})$ with a periodicity of $\Delta\omega = 4\pi/(N_b\ T_{bb})$ in the frequency spectrum, and is analogous to the well known spatial interference pattern of light passing through an array of multiple slits. This interference envelope function also has the property for mode K that betatron sidebands in the neighborhood of each global maximum will have zero or nearly zero amplitudes for all other N_b-1 modes. Therefore to find a spectral line for mode (L,K), which has minimum coupling to other modes, select one of the betatron sidebands that satisfies

$$\omega_{L,K} = (nN_t + L)\,\omega_r + \omega_\beta$$

where n is an integer and which is the nearest one to the interference function's global maxima, ω_I, where

$$\omega_I = \frac{(2\pi\, K + i\ N_b)}{N_b\ T_{bb}}$$

where i is an integer. So it is possible to find a single betatron sideband for each eigen mode which will best represent the dynamics of that eigen mode.

MEASUREMENT TECHNIQUES

Observations of dipole coupled bunch-train modes of oscillation were made using spectrum analyzers connected to horizontal and vertical processed BPM signals that were sufficiently broadband to be able to detect bunches with a 14 nsec spacing. The tracking generator output of the spectrum analyzers were connected to modulators, which can gate the generator signal on continuously or on for a pulse of duration one to a few milliseconds. The modulated signals are then fed to broadband drivers (either shaker magnets or stripline kickers.) To observe the tune shift as a function of beam current the analyzers were set to scan across the betatron sidebands corresponding to each bunch-train mode using a continuous excitation for the drivers. The frequency corresponding to either the spectral peak or, if different, the intensity weighted centroid of the spectrum were recorded. The damping rate measurements were made using the spectrum analyzers set up as narrowband receivers tuned to the same betatron sidebands with the drivers modulated on to excite the beam for a few milliseconds and then turned off to measure decay time of the amplitude of each mode. If there were no coupling to other bunch-train modes, we would expect this decay to be exponential over a few orders of magnitude. With the spectrum analyzer set up as a tuned receiver, the swept trace displayed the amplitude as a function of time and by recording two amplitude readings and their time difference, the damping rate could be calculated.

OBSERVATIONS

A large number of measurements of the tune shift and damping rate vs. positron current have been performed at CESR. The accelerator conditions corresponded to routine High Energy Physics operating parameters, i.e. beam energy of 5.3 GeV, horizontal tune of 10.541, vertical tune of 9.592, bunch length of 18 mm and a spacing of 28 nsec between bunches within a train. During these sets of measurements the bunches which were populated ranged from a single bunch (1t1b, i.e. 1 train 1 bunch) to 1t2b, 1t3b, 3t2b, 9t1b and 9t2b. The spacing between the first bunches in each of the trains were equal for 3 trains and had an extra 42 nsec between the last and first trains for 9 trains of bunches.

The betatron mode spectrum for trains of bunches has been observed for these cases and is in agreement with the predictions above. Figure 1 presents the example of 1 train of 2 bunches where one of the betatron spectral lines was excited and the resulting beam spectrum was observed for each of the bunch modes. The nodes of the frequency spectra are visible at 18 MHz for the K=0 mode and at 0 and 36 MHz for the K=1 mode as expected for a 28 nsec spacing between 2 bunches. The roll off of the amplitude at higher frequencies is due to the finite width of the BPM signal as processed for the spectrum analyzer.

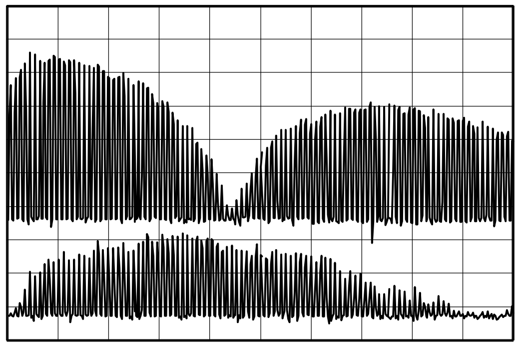

Figure 1: Betatron frequency spectra for the K=0 eigen mode (upper trace) and K=1 eigen mode (lower trace) for 1 train of 2 bunches with a 28 nsec spacing. Horizontal scale: 0 to 40 MHz. Vertical scale: 5 dB/division.

Typical results for the measurements of tune shift and damping rate vs. total beam current are presented in Figure 2A and 2B for the vertical eigen modes for the case of 9 trains of one bunch. The vertical tune shift data in figure 2A is plotted with an arbitrary offset for each of the eigen modes in order to separate them on the graph. Notice that all the eigen modes have essentially the same slope vs. current, a result which is typical of the horizontal and vertical tune shifts for all the cases studied. The vertical damping rates, α_v, in figure 2B have not been corrected for the small head-tail damping from chromaticity; the slopes of these damping rates do show a significant variation over the set of modes. Both of these sets of data were taken with the distributed ion pumps OFF to eliminate the predominantly horizontal effect known as Anomalous Antidamping (AA) [2]. Measured with the beam stabilization feedback system ON, figure 2C gives the difference in horizontal damping rates α_h for pumps ON minus OFF for all eigen modes again for 9t1b. Total beam currents in the range of 40-50 mA show the most extreme difference in α_h from mode to mode and in this range the instability is strongest becoming weaker at higher currents.

Measurements for 2 bunches per train found some added features. The spectrum of each eigen frequency is split into two separate peaks, one for the lead and one for the trailing bunch; this was easily observed in the vertical spectrum as these peaks are sufficiently narrow that the splitting can be a few times the width of the peaks. In the damping rate

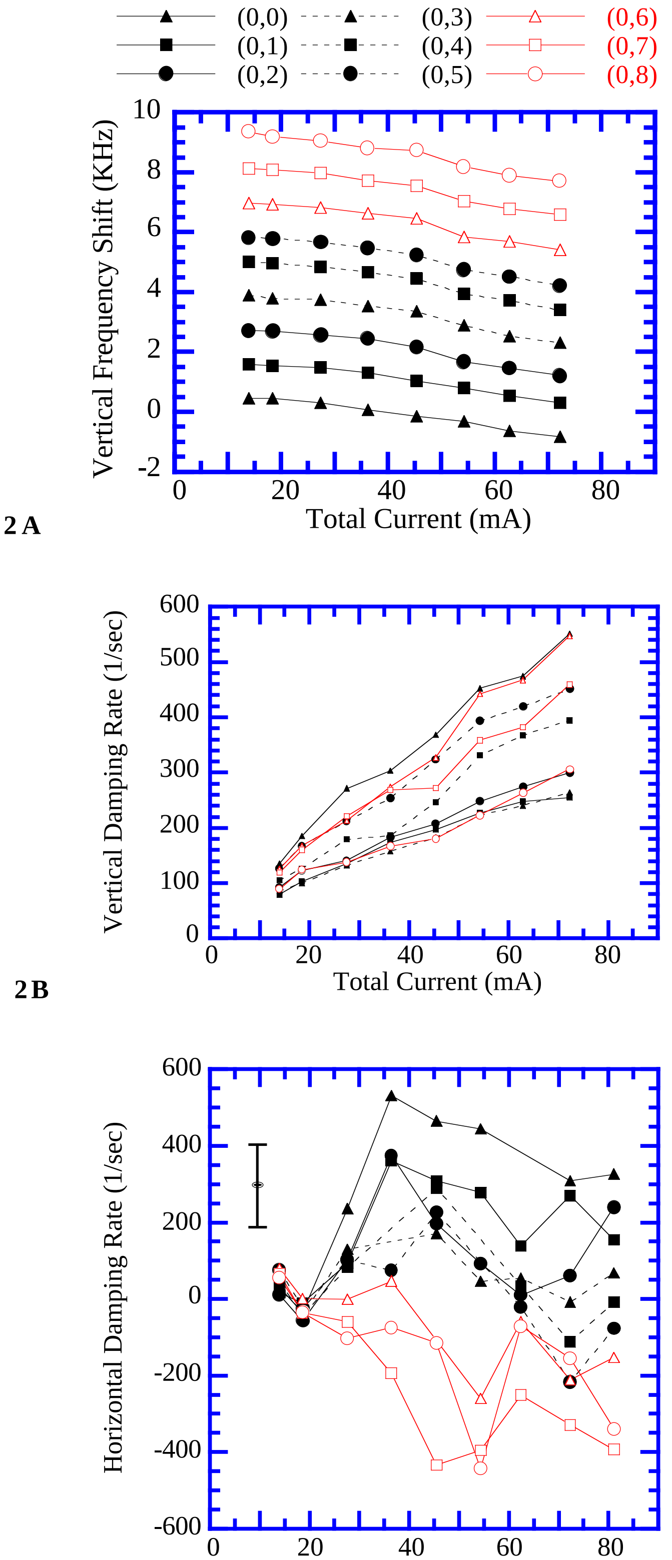

Figure 2: Vertical tune shift vs. total current (2A), vertical damping rate vs. total current (2B), and horizontal damping rate vs. total current (2C) shown for each of the 9 coupled train modes of oscillation (L,0) for 9 trains of a single bunch. Distributed ion pumps are OFF for figures 2A and 2B while figure 2C is the difference of pumps ON minus OFF.

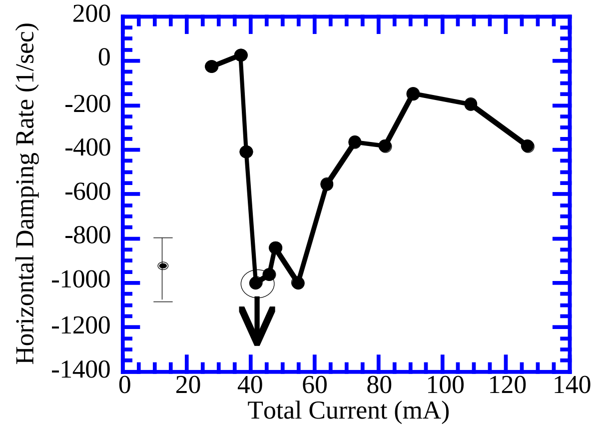

Figure 3: Horizontal damping rate difference for distributed pumps ON minus OFF vs. total beam current for the most unstable eigen mode in the case of 9 trains of 2 bunches. The circled point designates an upper limit for α_h at 42 mA.

measurements one observes an interference beat pattern in time at the difference frequency between the two spectral peaks which modulates the expected exponential decay. In the horizontal case this decay rate can be comparable to the decoherence time from the beating of the two betatron frequencies making damping rate measurements difficult and subject to larger systematic errors. Figure 3 shows α_h vs. current for 9t2b for the (L,K)=(8,0) eigen mode. Notice that the peak of the instability occurs at the same total beam current as the case of 9t1b; this implies that AA is affected by the total current per train or in other words the initial decay of the wakefield for AA is longer than 28 nsec.

All the measurements thus far have shown that AA will be the dominant mechanism for single beam instabilities for trains of single or multiple bunches. Since the present feedback system is able to stabilize the beam during filling as the current passes through the region of maximum instability, we can expect that this feedback system will be suitable for at least 5 bunches in 9 trains.

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