DEPENDENCE OF BEAM INSTABILITIES CAUSED BY ELECTRON CLOUDS AT CESRTA ON VARIATIONS IN BUNCH SPACING AND CHROMATICITY*

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Abstract

Experiments have been performed at the Cornell Electron-Positron Storage Ring Test Accelerator (CESRTA) to probe the interaction of the electron cloud with a 2.1 GeV stored positron beam. The purpose of these experiments was to characterize the dependence of beam–electron cloud interactions on the bunch spacing and the vertical chromaticity. These experiments were performed on a 30-bunch positron train, at a fixed current of 0.75mA/bunch. The bunch spacing was varied between 4 and 56 ns at three different vertical chromaticity settings. The beam dynamics of the stored beam, in the presence of the electron cloud, was quantified using: 1) a gated beam position monitor (BPM) and spectrum analyzer to measure the bunch-by-bunch frequency spectrum of the bunch trains; 2) an x-ray beam size monitor to record the bunch-by-bunch, turn-by-turn vertical size of each bunch within the trains. In this paper we report on the observations from these experiments and analyze the effects of the electron cloud (EC) on the stability of bunches within these different trains.

ELECTRON CLOUD INTERACTIONS

CESRTA has been studying the effects of ECs on stored beams to understand their impact on future low emittance storage ring and linear-collider damping ring designs. It is important to understand the way that the electron cloud alters the dynamics of bunches within the train. Measurements of the shift in the coherent betatron tunes from bunch to bunch along the train provide evidence for the change in EC density within the train.

Another question is how does the damping of the coherent motion of bunches change in the presence of the EC. One technique is to observe the BPM signal from a single bunch and to drive this bunch in one of its coherent modes, then turn off the excitation and measure the damping of the motion.[1] A second method is to observe the change in the spectral amplitude of the coherent modes as the damping is changed. In our case we chose to alter the damping by changing the chromaticity of CESR.

EXPERIMENTAL METHODS

Instrumentation at CESRTA allows the study of the position spectrum of individual bunches within the train by observing a single button of a BPM and gating the signal to accept only the bunch being studied[1]. This gated signal is routed to a spectrum analyzer, which averages the spectrum for approximately 10 seconds. Well above the noise baseline, this spectrum contains horizontal and vertical dipole (D) (m=0) betatron modes at frequencies F_h and F_v, in many cases vertical head-tail (HT) (m=±1) lines at $F_v \pm F_s$ (F_s is the synchrotron tune) and occasionally horizontal HT lines. Over some range of vertical chromaticity settings the amplitudes of the D and HT lines will decrease as the chromaticity increases. The observations presented here span a range of chromaticity settings where the coherent D and HT mode amplitudes vary as a function of chromaticity. By interpolating within these sets of measurements we arrive at approximately the same spectral D and HT mode amplitudes for the most unstable bunches thus allowing us to quantify the change in growth rate as we change the spacing between bunches within the train.

For a given spacing of bunches we filled each of the 30 bunches to 0.75 mA (1.1×10^{10} particles.) Initially we varied the chromaticity while observing the amplitude of at least one of the HT modes for bunch 25 (which is generally in the range of bunches exhibiting unstable motion) in order to determine a reasonable range for the chromaticity settings. We chose a value for the chromaticity within this range. We topped-off the beam, took spectra for five of the bunches and in parallel acquired turn-by-turn vertical beam size data for each bunch. At this point we top off the beam again and acquire the same data for the next five bunches. The set of data for all 30 bunches constitutes a data run. After examining the data online to verify its quality, we changed the chromaticity and/or bunch spacing and began a new data run.

In addition we took calibration data with a single positron bunch. The first measurements calibrated the chromaticity as a function of the control console knob setting by measuring the change in betatron tunes as the RF frequency was changed. The second is called drive-damp measurements, in which a single bunch is excited with a stripline transverse kicker on resonance at one of its coherent modes. If this is one of the HT modes, then

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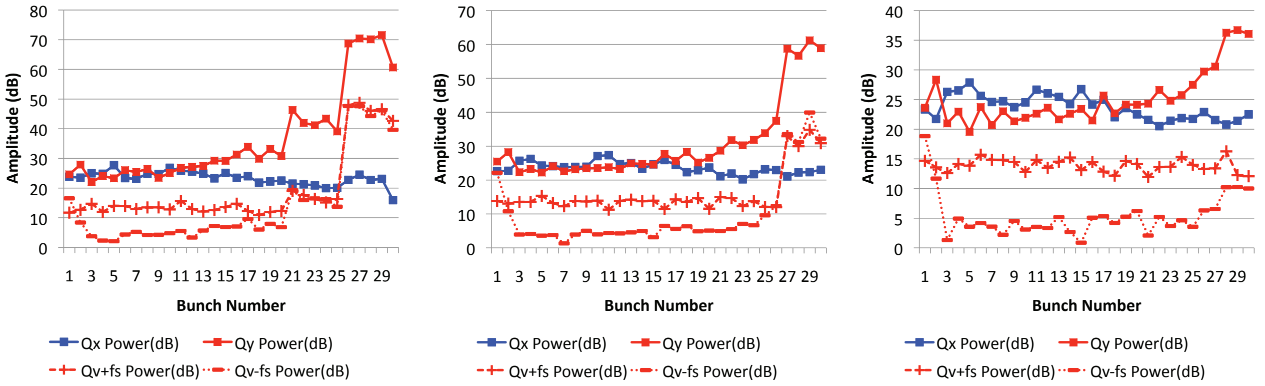

Figure 1: Amplitudes of the horizontal D mode (Q_x Power), vertical D mode (Q_y Power), vertical HT modes ($Q_y \pm f_s$ Power) for the 30 bunches in 8 ns-spaced trains for three chromaticities, Q_y'=-0.53 (left), Q_y'=-0.43 (center) and Q_y'=-0.34 (right).

we also excite the bunch longitudinally with a cavity kicker to produce an energy variation to the transverse kick. The transverse kicker is driven for approximately 1 ms and then turned off for a few tens of ms to allow the coherent motion to damp. Using a spectrum analyzer operating as a tuned receiver, we determine the damping time of the motion from a linear fit of the amplitude (in dBm) vs. time. Drive-damp measurements are performed for different settings of the vertical chromaticity. Both sets of data were fit to lines.

DATA ANALYSIS

After acquiring data for the runs, we processed it offline to produce Gaussian fits to the spectral peaks (in dB relative to the noise floor) at each of the D and HT modes for each bunch. These fits yielded the mode frequency, amplitude and width. (The focus of this paper is on analysis of the spectrum; the analysis of the data from the vertical beam size measurements is discussed elsewhere. [2]) An example of the spectral amplitudes for these modes is displayed in Figure 1 for 8 nsec-spaced bunches for three values of vertical chromaticity (defined as $Q_v' = dQ_v/d\delta$ where Q_v is the vertical tune and δ is the fractional change in energy.) From these plots one sees that the amplitudes of the coherent modes generally grow as the bunch number within the train increases. The stair-step pattern visible in the left-hand plot of Figure 1 occurs because we only topoff the beam current every fifth bunch. (For bunch spacings of 12 nsec or less the amplitudes of the m=-1 HT mode are larger for the first bunch or bunches in the train. This phenomenon is discussed elsewhere. [3]) Although one would expect the full width at half maximum (FWHM) of the spectral peaks would be a better indication of the stability of the bunch for each coherent mode of oscillation, we find that this is not the case. We have observed that for later bunches within the train the shape of the lines tends to split into two modes, whose separation increases with bunch number [4]. Since it is difficult to resolve the widths of these modes for many of the bunches, the FWHM of the peaks of less useful as a measure for bunch stability.

Determination of the Same Coherent Amplitudes

For each spacing of bunches within the train we determined the vertical chromaticity that would correspond to a particular oscillation amplitude one-by-one for each of the three coherent modes by employing the following procedure. 1) Determine a "typical" maximum coherent oscillation amplitude for each data run by finding the maximum amplitude for this mode. Average its amplitude (in dB) with that of all other bunches that have amplitudes within a "threshold" value of the maximum amplitude (e.g. 5 dB). 2) Fit the "typical" amplitudes in dB vs. the 3 chromaticity settings with a line. 3) After completing this fitting for each coherent mode and for all bunch spacings, select a "reference amplitude" within the range of measured amplitudes for each mode. 4) Interpolate to find value for the chromaticity, which matches the reference amplitude. 5) We expect that the value of chromaticity determined for each mode of oscillation would produce the same coherent oscillation amplitude for every bunch spacing.

Having found values of vertical chromaticity for the D and HT modes, which should produce the same oscillation amplitudes, we next translate this chromaticity setting to the associated coherent damping rate. Using the linear fits from the drive-damp measurements of Dec. 2011 [4],

$$\alpha_V = -\left\{\left(-3\ \mathrm{sec}^{-1}\,\mathrm{mA}^{-1} Q_V'\right)\left(\frac{I_b}{1\ \mathrm{mA}}\right) + 110\,\mathrm{sec}^{-1}\right\}$$

$$\mathrm{V\,dipole}\,(m = 0)\ \mathrm{mode}$$

$$\alpha_V = -\left\{\left(21\ \mathrm{sec}^{-1}\,\mathrm{mA}^{-1} Q_V'\right)\left(\frac{I_b}{1\ \mathrm{mA}}\right) + 4\,\mathrm{sec}^{-1}\right\}$$

$$\mathrm{V\,dipole}\,(m = -1)\ \mathrm{mode}$$

$$\alpha_V = -\left\{\left(17\ \mathrm{sec}^{-1}\,\mathrm{mA}^{-1} Q_V'\right)\left(\frac{I_b}{1\ \mathrm{mA}}\right) + 33\,\mathrm{sec}^{-1}\right\}$$

$$\mathrm{V\,dipole}\,(m = +1)\ \mathrm{mode}$$

we determined the corresponding damping rates.

To provide a sense for the accuracy of this analysis, we varied the "threshold", which was used to select the range of oscillation amplitudes below the maximum amplitude that were averaged to determine the "typical" maximum amplitude. The threshold was stepped between 2 and 6 dB in 0.5 dB increments and then steps 2) through 5) above were repeated. The sets of chromaticities computed by this process were used to calculate the associated coherent damping rates. In Figure 2 the average of these damping rates and their standard deviations for the D and HT modes vs. bunch spacing are plotted. All points have error bars for the standard deviations although most of these are smaller than the size of the data points. Points with large error bars imply that at least one of the "typical" oscillation amplitudes used for the calculation for that point was very sensitive to which bunch amplitudes were included in the averaging. This implies that damping rates with visible error bars are not determined accurately, nonetheless they are included in the plots for completeness. It should be mentioned that there are two different measurements for the 14 nsec bunch spacing; the second taken about one year after the first. The second of these measurements is plotted slightly to the right of the first in figure 2 and it provides some confidence in the reproducibility of these measurements over longer times.

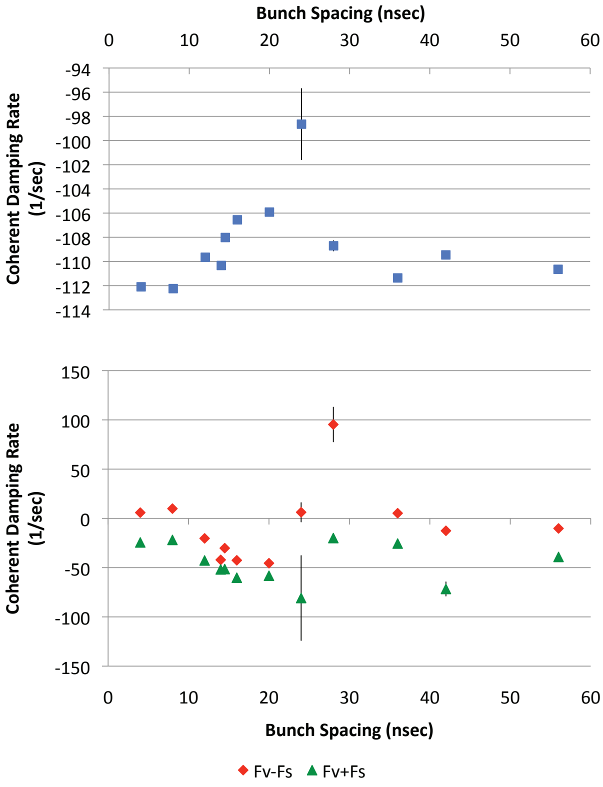

Figure 2: Variation of coherent damping rates for D modes (upper) and HT modes (lower) to produce equal amplitudes of oscillation for each of the modes as a function of the spacing between bunches in 30 bunch-long trains of 0.75 mA per bunch.

CONCLUSIONS

The results of these measurements and analyses as shown in Figure 2 allow us to draw a few conclusions. Both plots show some deviation away from a constant damping rate for trains having spacings between 8 and 28 nsec. The deviation for the dipole mode is fairly small (approximately 6 sec^{-1} or less than 50% of the radiation damping rate) and is in the direction to slightly increase the damping of the dipole coherent motion. However, for both of the head-tail modes the deviation from a constant damping rate is much more pronounced yielding between 40 and 50 sec^{-1} of *growth* rate over much of the same range of bunch spacings. Since the larger amplitudes typically occur for the later bunches, this implies that the HT modes are less stable for the later bunches within trains, which have spacings between 8 and 28 ns. Based on retarding field analyzer measurements, we have evidence of a multi-pacting resonance within the normal CESR dipole magnets [5]. The resonance is produced in the dipoles by electrons from the EC being accelerated and spiraling along the magnetic field lines to produce secondary electrons at the top and bottom walls, which then arrive back at the beam's orbit with some delay. The EC, enhanced by the wave of secondary electrons, interacts more strongly with succeeding bunches if the bunch spacing is approximately the same as the flight time of the electrons. For the beam parameters above and the dipole field strength at 2.1 GeV in CESR we would expect the resonance to have a period of approximately 10 ns [5], which is roughly the bunch spacing for trains where the growth rate of the HT modes is greatest.

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