DEPENDENCE OF THE COUPLING OF DIPOLE MOTION FROM BUNCH TO BUNCH CAUSED BY ELECTRON CLOUDS AT CesrTA DUE TO VARIATIONS IN BUNCH LENGTH AND CHROMATICITY*

J. A. Crittenden†, L. Y. Bartnik, M. G. Billing, M. J. Forster, N. T. Rider, J. Shanks, M. Spiegel,
S. Wang, CLASSE, Cornell University, Ithaca, NY, U.S.A.,
R. L. Holtzapple, California Polytechnic State University, San Luis Obispo, CA, U.S.A.,
E. C. Runburg, Notre Dame University, Notre Dame, IN, U.S.A.

Abstract

The Cornell Electron-Positron Storage Ring Test Accelerator (CESRTA) has conducted experiments to probe the interaction of the electron cloud (EC) with a 2.1 GeV stored positron beam. These experiments investigate the dependence of beam–electron cloud interactions vs. bunch length (or synchrotron tune) at two values of the vertical chromaticity. The experiments utilized a 30-bunch positron train with a 14 ns spacing, at a fixed current of 0.75mA/bunch. The beam dynamics of the stored beam, in the presence of the electron cloud, was quantified using: 20 turn-by-turn beam position monitors in CESR to measure the correlated bunch-by-bunch dipole motion and 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 a more detailed analysis for the coupling of dipole motion via the EC from each bunch to succeeding bunches in the train.

INTRODUCTION

Since 2008 the storage ring CESR has operated as a test accelerator, CESRTA, to study EC effects in the presence of trains of positron or electron bunches [1,2,3]. One set of measurements was the study of the dependence of electron cloud (EC) dynamics on the bunch length (equivalently synchrotron tune). The result of these measurements found no significant dependence over a limited range of synchrotron tunes (see Section 6.3.2.9 in reference [4]) in disagreement with observations and simulations made elsewhere[5]. Thus it was decided to revisit these measurements over a larger range of synchrotron tunes and to study the EC as a function of two vertical and horizontal chromaticities to allow for a variation in damping rates.

Gated horizontal (H) and vertical (V) strip-line kickers were utilized to drive coherent dipole motion in single bunches within the train, allowing the observation of any coupling of the motion of these bunches to subsequent bunches due to the EC. The motion is then observed at 20 CESR beam position monitors (CBPM)[6], which simultaneously detect the positions of all bunches turn-by-turn for 8192 turns at a revolution frequency of 390 kHz. Since the growth of the EC within the train shifts the tunes of the bunches monotonically along the train. As the excitation was moved from one bunch to the next the driving frequency for the kickers was swept over a range of frequencies sufficient to cause both H and V motion for every bunch. The 8192 turns encompassed two periods of the frequency sweep to guarantee one complete period was observed for the excitation and decay of the dipole motion.

EXPERIMENTAL PROCEDURES

CESR operated at 2.085 GeV in low-emittance conditions for measurements in December 2015 and April 2016. The tunes of CESR for the first positron bunch were set to be Q_x=14.572 and Q_y=9.579, to attempt to avoid placing any of bunches within the train on a resonance. The V emittance was adjusted for a single bunch to be approximately 37 pm-rad (with the design H emittance of 3.2 nm-rad). The measurement sequence is described in some detail elsewhere[7] with bunch-by-bunch CBPM measurements taken for all bunches, which had the first bunch excited, and then the second bunch excited and so on through the entire train. Measurements were taken for stored currents of 0.75 mA (1.1×10^{10} particles) per bunch.

Table 1: Conditions for Different Data Sets (Scenario #'s)

Scenario #	Q_s	σ_z (mm)	Q'_h	Q'_v	Relative Excitation
1602	0.025	27.3	0.6	4.0	3
1603	0.025	27.3	3.9	9.6	3
1666	0.040	17.3	0.6	4.0	1
1668	0.040	17.3	3.9	9.6	1
1671	0.050	13.6	0.6	4.0	1
1670	0.050	13.6	3.9	9.6	1
1607	0.064	10.8	0.6	6.3	1.5
1608	0.064	10.8	3.9	9.6	1.5

During the measurements, the synchrotron tune, Q_s, and bunch length, σ_z, were adjusted to four settings as seen in Table 1. The measurements were performed at different values of vertical chromaticity $Q_v' = \partial Q_v / \partial \delta$, where δ is the fractional energy deviation. In these optics the V damping rates for 0.75 mA bunches were measured to be 79, 124 and 189 sec^{-1} for the three Q_v' settings in Table 1. (These are much higher than the transverse radiation damping rates of 18 sec^{-1}.) The last column in Table 1 represents the relative excitation sent to both the H and V

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† jac243@cornell.edu

strip-line kickers. It was necessary to vary the drive level to maintain good beam lifetimes during data acquisition.

ANALYSIS METHOD

The turn-by-turn CBPM data was recorded for 10 adjacent beam position monitors (BPMs) on each the east and west sides of CESR. BPM data for each bunch's trajectory was fit over 42 turns to free betatron and synchrotron motion [8], using the design optics between BPMs on each side of CESR and accounting for the operating tunes by correcting the phase advance between the two sets of BPMs. The fitting begins at a time T_f after the maximum displacement was achieved for the driven bunch. The 42-turn window is then shifted in 7 turn increments, producing a time sequence for the fits. The fitting of the trailing bunches also began at T_f. In each window the results of the fits yield the betatron tune of the bunch, its oscillation amplitude and starting betatron phase (as projected to the positron injection point of CESR). Examples of the fitting may be found elsewhere[7].

PRELIMINARY RESULTS

After fitting the trajectories, the damping rate, α, of the oscillation amplitude, A, vs. time, t, was determined using

$$\alpha\ (t-t_0)=2\ln\left(\frac{A}{A_0}\right)$$

where A_0 corresponds the maximum amplitude (at time t_0) and t is allowed to range through the decay time of the motion. This gives a reasonable fit to the average decay rate even when there is a beating in the oscillation amplitude during the decay. After determining the average tunes and damping rates for all bunches during the decay time, the fits were examined to remove incorrectly fit data from consideration. These include bunches where the automatic trajectory fitting failed. They also contained bunches where the trajectory fitting succeeded, but the induced oscillation was too small, or there was an apparent failure in the automatic data acquisition system leading to the wrong periodicity for the excitation or underdamped oscillations. Overall about 20% of the data was removed from these preliminary results due to fitting inconsistencies.

For each set of conditions the tunes and damping rates were plotted versus the excited bunch number for three bunches (the excited bunch, the first and second bunches trailing the excited bunch.) To determine the average incremental effect of the EC per bunch within the train a linear fit for the tunes and damping rates vs. bunch number was performed for the three bunches for each set of conditions. Figure 1 displays bar graphs for the H and V directions for the slope of the frequency shift per bunch for the three bunches and the eight sets of conditions. In the H plane the tune shifts are relatively large (0.12 to 0.25 kHz per bunch) and fairly similar for the excited bunch and trailing bunches. There may be a trend for the lower values of Q_s (longer bunch lengths) that the larger values of H chromaticities produce a smaller tune shift.

In the V plane the tune shifts per bunch are generally much smaller than those in the H plane. Also note there are several cases where a larger, negative V tune shift is observed. In these cases the coherent V tunes appear to transition to a fixed value for later bunches in the train. Figure 2 shows an example of this behavior for scenario 1608. Note that V tunes of later bunches in the train appear to "lock onto" a tune around 220 kHz. If this is indicative of a corresponding resonance, the numerology suggests that this must be a fairly high order resonance. In CESR the large H tune shift and much smaller V tune shift is typically observed for EC (for example see section 6.3.2.3 in reference[4].)

Figure 1: Bar graphs of the linear fits for the horizontal (upper) and vertical (lower) tune shifts per bunch (in kHz per bunch) for the 8 sets of beam conditions for the excited bunch and first and second trailing bunches.

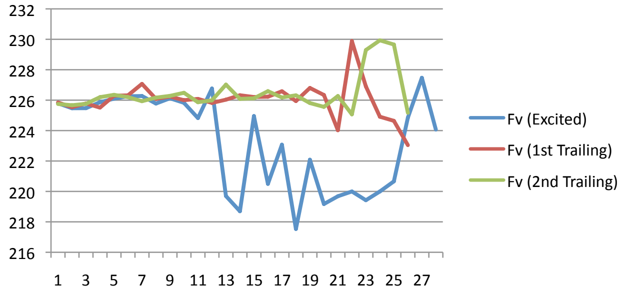

Figure 2: Example of the vertical tunes vs. bunch number for the excited bunch and first and second trailing bunches. This is for scenario number 1608.

When calculating the damping rate for each bunch, there is currently considerably more scatter than for the tune shift due to the fitting of the derivative of amplitude and this should be recalled while examining the results presented below. Figure 3 presents the bar graphs for the fitted damping rate per bunch for the 8 sets of data. Recalling that the radiation damping rate for all bunches is 18 sec^{-1}, notice that the change in damping rate per bunch is comparable to or larger than this scale in the H direction. The rate of change of the V damping rates per bunch is typically smaller than the H damping rates. In both cases it is difficult to see any significant trends for the rate of change of the damping rates vs. Q_s (bunch length) or chromaticity. There may be an indication that coherent damping rates for the trailing bunches may be larger than the excited bunch on the average, but any conclusion along this line would require further analysis.

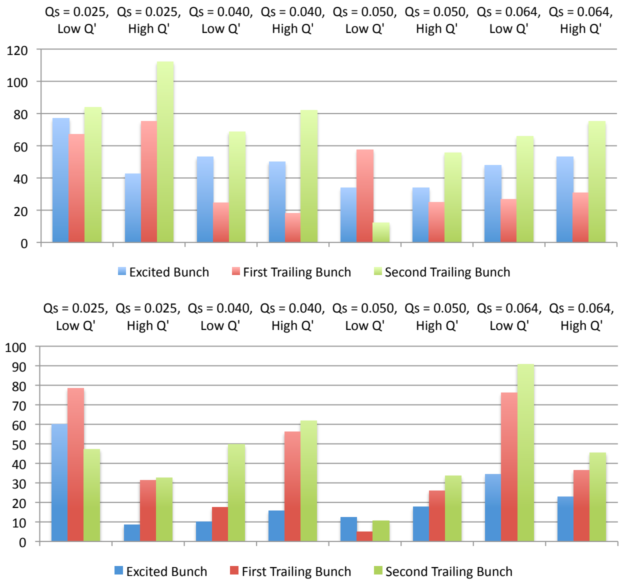

Figure 3: Bar graphs of the linear fits for the horizontal (upper) and vertical (lower) damping rates per bunch (in sec^{-1} per bunch) for the 8 sets of beam conditions for the excited bunch and first and second trailing bunches.

CONJECTURES BASED ON THE OBSERVATIONS

The results for the tune shifts and damping rates per bunch for the 8 sets of conditions for positron bunch trains are much larger than the results for electron trains in the equivalent conditions[9]. It is well known that, since the EC is concentrated around the positron beam's trajectory and is virtually absent around the electron beam's trajectory, the tune shift per bunch is indicative of the growth of the EC density along the positron train (see section 6.3 in reference[4].) The much larger growth of the damping rate through the train for a positron beam when compared to an electron beam, suggests that the EC provides a damping mechanism for coherent motion of bunches within the trains. In CESR this EC coherent damping appears to be stronger in the H direction as compared to the V direction. Since CESR is a horizontal dipole-dominated ring, it is reasonable to conjecture that the H damping may be stronger since the EC density waves produced by the bunches' passage are constrained to spiral around the vertical magnetic field lines: As a horizontally oscillating positron bunch passes through the EC in a dipole, the electrons are accelerated to impact the top and bottom of the vacuum chamber walls and producing secondary electrons, which travel along the field lines to produce an EC density wave, centred on the H position of the original positron bunch. It is this effect, which excites trailing bunches in the horizontal direction, since the magnetic field lines constrains the EC density wave to follow the H position of the exciting bunch. This may allow the non-linearities of the EC density to decohere the H motion of the trailing bunches. For oscillations of the excited bunch in the V direction in the dipoles, the EC is still constrained to impact the top and bottom of the chambers, but now the V deflection of the trailing bunches is determined by the difference in the arrival times of the EC density waves from the secondary electrons produced on the top and bottom of the chamber. Since there is a large energy spread in the secondary electrons the difference in the arrival times of EC density waves from the top and bottom is more smeared out in the V direction. Also the V beam size is much smaller than the H size. One could conjecture that the combined of a more smeared out EC density wave and a much smaller phase space region in the vertical direction may produce less non-linearities and, hence, decoherence of the bunches' motion in the V direction. This would imply that there would be more damping in the H direct with respect to the V direction. It is interesting to anticipate the day, when it is possible to simulate the EC-beam interaction taking into account the dynamics of the EC density waves and thus to address these conjectures.

CONCLUSIONS

This paper along with its companion paper[8] has shown that ECs provide a mechanism for the damping of coherent motion as the EC density increases in the dipole-dominated storage ring, CESR. The observations presented here can not be attributed to wakefields. There does not appear to be a significant correlation of the tune shift per bunch and change in damping rate per bunch with bunch lengths over the range of 10.8 to 27.3 mm or chromaticity changes in the range of 4 to 5. These results are in agreement with earlier measurements (see Section 6.3.2.9 in reference [4]).

Although there are several improvements that can be applied to the data acquisition process and to the analysis techniques, the methods described in this paper provide an experimental mechanism for measuring the interaction of positron bunches in trains with EC density waves. These observations may be important for testing future EC-beam dynamics simulations.

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