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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*

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Abstract

The Cornell Electron-Positron Storage Ring Test Accelerator (CesrTA) has been utilized to probe the interaction of the electron cloud with a 2.1 GeV stored positron beam. Recent experiments have characterized any dependence of beam–electron cloud (EC) interactions on the bunch length (or synchrotron tune) and the vertical chromaticity. The measurements were performed on a 30-bunch positron train with 14 nsec spacing between bunches, at a fixed current of 0.75 mA/bunch. The dynamics of the stored beam, in the presence of the EC, was quantified using 20 turn-by-turn beam position monitors in CESR to measure the correlated bunch-by-bunch dipole motion. In this paper we report on the observations from these experiments and analyze the coupling of dipole motion from bunches within the train to subsequent bunches, caused by the EC.

INTRODUCTION

In 2008 the storage ring CESR was converted to operate as a test accelerator CesrTA, capable of studying EC effects in the presence of trains of positron or electron bunches [1,2,3]. Early in the CesrTA project measurements were undertaken to study any dependence of electron cloud (EC) dynamics on the bunch length (equivalently synchrotron tune). The result of these studies found no significant dependence over a limited range of synchrotron tunes (see Section 6.3.2.9 in reference [4]). These results disagreed with observations and simulations made elsewhere [5]. As a consequence it was decided to revisit these measurement over as large a range of synchrotron tunes as practical as well as study the EC as a function of two vertical and horizontal chromaticities to allow for different damping rates.

In addition, gated horizontal and vertical stripline kickers were employed to excite coherent dipole motion in single bunches within the train in order to observe any coupling of the motion of these bunches to subsequent bunches through the EC. The motion is then observed at 20 monitors from the CESR beam position monitoring (CBPM) system [6], which simultaneously detect the positions of all bunches turn-by-turn for 8192 turns as the excitation was moved from one bunch to the next through the entire train. Since the growth of the EC within the bunch shifts the tunes of the bunches monotonically along the train, the excitation frequency for the kickers was swept over a range sufficient to cause both horizontal and vertical motion in every bunch. The number of turns, observed by the CBPM system, was set to encompass 2 periods of the frequency sweep to guarantee one complete period for the excitation and decay of the dipole motion.

EXPERIMENTAL PROCEDURES

CESR was operated at 2.085 GeV in low-emittance conditions for measurements, taking place in December 2015 and April 2016. Bunch-by-bunch transverse and longitudinal dipole feedback was available; bunch-by-bunch feedback was employed during injection and it was either disabled or reduced during measurements as described below. The tunes of CESR for the first positron bunch were set to be Q_x=14.572 and Q_y=9.579, chosen to avoid placing any of bunches within the train on a resonance. After optics correction the vertical emittance was adjusted for a single bunch to be approximately 37 pm-r (for a design horizontal emittance of 3.2 nm-r). The measurement sequence was 1) to top off all bunches with all feedback on, 2) turn off transverse feedback, 3) to transversely excite in sequence 5 bunches individually while taking CBPM data for each excitation. Steps 1-3 were repeated until all 30 bunches have been excited. During the entire experiment longitudinal feedback remained on. During filling horizontal and vertical damping rates were 2700 sec^{-1} and 6100 sec^{-1}, respectfully, for 0.75 mA ($1.1x10^{10}$ particles). These are much higher than the 18 sec^{-1} transverse radiation damping rates.

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 with the same vacuum chamber components (hence impedance) the change in vertical damping rates were measured in December 2014 at σ_z=10.8 mm as a function of Q_v',

$$\Delta\alpha_v = \left(26.2\ \mathrm{sec}^{-1}\right) Q_v' \left(\frac{I_b}{1\ \mathrm{mA}}\right)$$

yielding incremental changes in the vertical damping rates for 0.75 mA bunches of 79, 124 and 189 sec^{-1} for the three Q_v' settings in Table 1. The last column in Table 1 represents the relative amplitude of the drive sent to both the horizontal and vertical stripline kickers. It was necessary to increase the lower vertical chromaticity and to

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decrease stripline deflections for some measurements to maintain good beam lifetimes during data acquisition.

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
1670	0.050	13.6	3.9	9.6	1
1671	0.050	13.6	0.6	4.0	1
1607	0.064	10.8	0.6	6.3	1.5
1608	0.064	10.8	3.9	9.6	1.5

ANALYSIS METHODS

The turn-by-turn CBPM data was recorded for 10 beam position monitors (BPMs) on each the east and west sides of CESR. BPM data was analyzed by fitting each bunch's trajectory over 42 turns to free betatron and synchrotron motion [7], using the design optics between BPMs on each side of CESR and correcting for the actual phase advance between the two sets of BPMs and operating tunes. Since the driven bunch was excited to its maximum amplitude over many turns, the fitting began at a time T_f after the maximum displacement was achieved for the driven bunch. The 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 fitting yields an oscillation amplitude and starting betatron phase, projected to a single location in CESR (chosen to be the positron injection point). Each window's fit also gives the betatron tune.

PRELIMINARY RESULTS

Figure 1 shows an example of the fitting results for the excited bunch (bunch 8 for Scenario 1666). For this bunch the decay is approximately exponential with different damping times for the horizontal and vertical motion, having initial, peak amplitudes of 0.4 mm and 0.3 mm, respectively. The next excitation by the stripline kicker is visible, beginning around turn 4000. Compare this with Figs. 2 and 3, which are the fits for bunches 9 and 10, the first and second trailing bunches, respectively, (for Scenario 1666), when bunch 8 was excited. Notice that there is delay in the growth of the amplitudes of bunches 9 and 10 and their peak vertical amplitudes are both comparable to the bunch 8's. The horizontal amplitude of bunch 9 is much less than either bunch 8 or bunch 10; the decay of this amplitude for bunch 10 shows a beat frequency of 220 Hz. Oscillations in the amplitudes are seen for many of the excited and trailing bunches, with their frequencies varying from roughly 100 Hz to 8 kHz. Some of these frequencies correspond to tune differences between the excited and trailing bunches; others may correlate with xy tune differences. Many are not explained at this time.

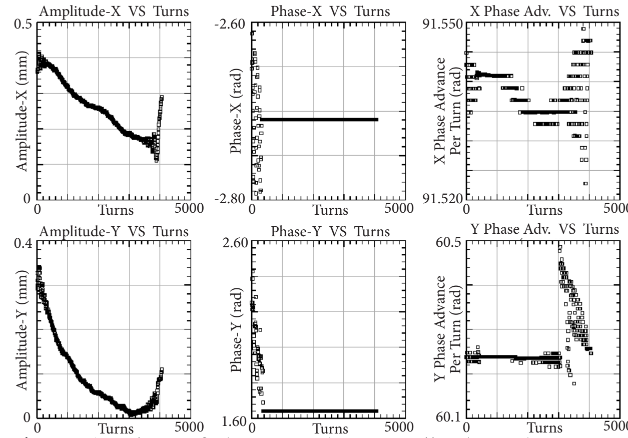

Figure 1: Plots of the x- and y- amplitudes, phases and tunes for the excited bunch, number 8 of 30.

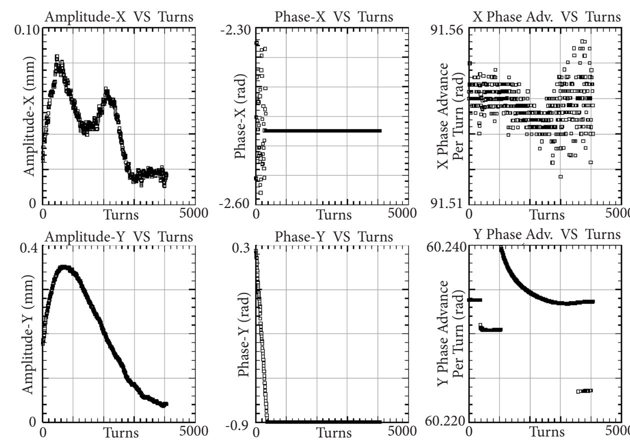

Figure 2: Plots of the x- and y- amplitudes, phases and tunes for bunch number 9, when bunch 8 is driven.

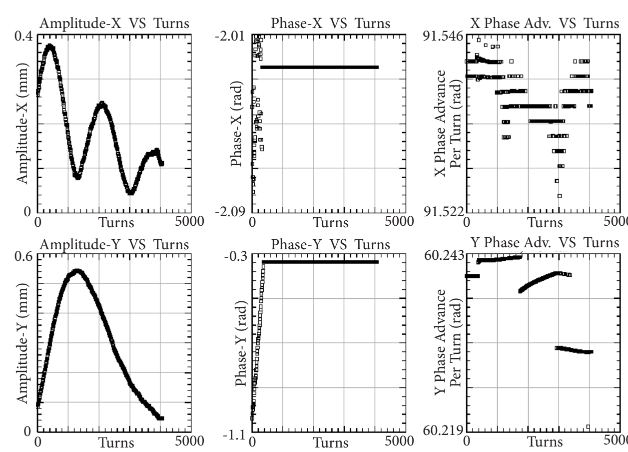

Figure 3: Plots of the x- and y- amplitudes, phases and tunes for bunch number 10, when bunch 8 is driven.

When examining the general characteristics of the x- and y-oscillation amplitudes in Fig. 4, it is noticed that the damping times decrease as the excited bunch number increases; this is true for excited and trailing bunches. For the same stripline deflections, the excited bunch's peak oscillation amplitude decreases as the excited bunch number increases. Since the EC increases through the train, these two observations suggest that the bunches' interaction with the EC provides some form of damping for coherent dipole motion. Figure 4 also shows the EC provides a mechanism to couple the motion of excited bunch to the trailing bunches with the risetime of the trailing bunches' motion decreasing as the excited bunch number increases. Based on earlier simulations for EC (see Fig. 6.41 and 6.42 in Reference [4]), the observed horizontal tune shifts of the excited bunches through the train are scaled to give an average EC density varying from approximately zero to 2.5×10^{12} m^{-3} in CESR. The increase of the rate of rise of the dipole motion, coupled from the excited bunch to the trailing bunches via the EC, appears to be correlated with the increase in EC density.

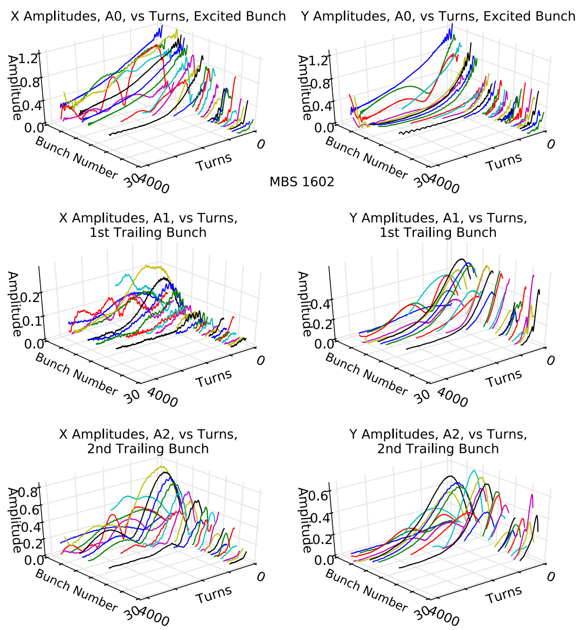

Figure 4: Amplitudes in the x- (left column) and y- (right column) directions vs. turns and vs. the excited bunch number for the excited bunch (top), first trailing bunch (middle row) and second trailing bunch (bottom) for Scenario 1602.

The observation of relatively less horizontal motion of the first trailing bunch compared to the second trailing bunch as seen in Figs. 2 and 3 also appears consistently in Fig. 4. Since the majority of CESR's circumference is dipoles, our conjecture suggests the EC, pinned to the dipoles' vertical magnetic field lines, may play a significant role for this behavior. If we assume the EC, generated by earlier bunches, has collected around the beam's trajectory, as the excited bunch is displaced vertically with respect to the trajectories of the earlier bunches, it will accelerate a different number of electrons from the cloud up vs. down in the beam pipe. The acceleration from the charge in the bunches will cause the electrons to hit the top and bottom walls of the vacuum chamber (±25 mm) in less than 1 nsec. The resulting secondary electrons will travel vertically as a EC density wave back toward the beam's axis, arriving over 30 nsec later for typical average secondary electron energies of 1.1 eV (see equations 5.1 and 5.2 in reference [4]) and any top-bottom asymmetry of this density wave will deflect the first trailing bunch vertically as the forces are largely in the vertical direction. If, instead, the excited bunch is off axis in the horizontal direction, the electrons from the EC will be again accelerated toward the top and bottom vacuum chamber walls, however at different horizontal position. Resulting secondary electrons stream back along vertical magnetic field lines as a density wave and will be displaced roughly half the distance to the walls for the first trailing bunch, producing a relatively small horizontal deflection. However, the first trailing bunch will tend to attract the EC density wave toward the axis with the density wave arriving on-axis approximately when the second trailing bunch arrives. The on-axis EC density wave will tend to deflect the second trailing bunch in the horizontal direction much more strongly. Thus the EC coupling from the excited bunch to trailing bunches would be expected to initially be strongest for the first bunch in the vertical direction and the second bunch in the horizontal direction.

The data contains examples of damping rates of the oscillation amplitudes varying from 40 to 2100 sec^{-1} in horizontal and 120 to 3200 sec^{-1} in the vertical for excited bunches (to be compared with 18 sec^{-1} for synchrotron radiation damping). These are generally lowest for the first bunch and increasing as the bunch number in the train increases. Since the EC decays in the dipole and drift sections of CESR in the gap between the end of the train and the first bunch on the next turn (see section 6.3.1 in reference [4]), tunes and damping rates of the first bunch should be unperturbed. Thus the damping rate change with vertical chromaticity for the lead bunch of the train should scale as shown above. However, these measurements suggest the change of damping rates is 2 to 3 times larger for the vertical chromaticity change. Remnant EC in the quadrupoles [8] may be responsible for this effect.

CONTINUING ANALYSIS

At the present state of the analysis there does not appear to be a strong dependence on bunch length for all of the phenomena described above. However, there is still more work required to finish the analysis of this data. This includes improvements to the fitting of the trajectories, more detailed fits of the rate of rise and fall of the amplitudes of oscillations for the trailing bunches also accounting for beat frequencies in the amplitudes. In addition it would be interesting to explore the possibility of producing a model for the coupling of motion from the excited bunches to the trailing bunches via ECs. Finally it may also be useful to study the amplitude dependence of the bunch-to-bunch coupling through the EC, since this may give some indication of the EC density in the neighbourhood of the trajectory of the positron bunches.

CONCLUSION

The technique of exciting single bunches within the train of positron bunches appears to be useful for exploring the interaction of ECs with trailing bunches. More effort is warranted to understand what information may be gleaned from this measurement method.

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