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

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Abstract

Earlier experiments at the Cornell Electron-Positron Storage Ring Test Accelerator (CESRTA) have probed the interaction of the electron cloud (EC) with a 2.1 GeV stored positron beam. Since a low EC density is expected with the electron bunches, their results characterize the dependence of beam–vacuum chamber impedance interactions, which are common to both positron and electron beams. The experiments were performed on a 30-bunch electron trains with a 14 ns spacing, at a fixed current of 0.75mA/bunch, at two different vertical chromaticity settings and for four different bunch lengths (or synchrotron tunes.) 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 analysis of the observations from these experiments and compare them with effects of the EC on the positron beam's dipole motion and coupling of the motion from each bunch to its succeeding bunches.

INTRODUCTION

In 2008 the storage ring CESR was converted to operate as a test accelerator CESRTA, to study EC effects in the presence of trains of positron or electron bunches [1 - 3]. Early measurements studied the dependence of electron cloud (EC) dynamics on the bunch length (equivalently synchrotron tune). 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]. In 2015 it was decided to revisit these measurements spanning a larger range of synchrotron tunes and to study the EC as a function of two vertical (V) and horizontal (H) chromaticities to allow for a variation in damping rates. In addition, since CESR can store counter-rotating electron bunches in exactly the same optics, measurements were undertaken to directly compare positron and electron beams in the same conditions in order to separate any other intensity-dependant effects from those of the EC dynamics.

Gated stripline kickers were utilized to drive coherent H and V dipole motion in single bunches within the train to allow the observation of any coupling of the motion of these bunches to later bunches due to wake-field effects. The motion is then detected at 20 CESR beam position monitors (CBPM)[6], which simultaneously measure the positions of all bunches turn-by-turn for 8192 turns at a revolution frequency of 390 kHz. Since bunch-to-bunch wake-fields coupling can shift the tunes of the bunches 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 sufficient to cause both H and V motion for every driven bunch. The 8192 turns encompasses two periods of the frequency sweep to guarantee one complete period for the excitation and decay of the dipole motion.

EXPERIMENTAL PROCEDURES

In December 2016 CESR operated in low-emittance conditions at energy of 2.085 GeV for these measurements. The tunes of CESR for the first electron bunch were set at Q_x=14.568 and Q_y=9.583, to avoid placing any of bunches within the train on a resonance. The V emittance was adjusted for a single bunch to be approximately 40 pm-rad (with the design horizontal emittance of 3.2 nm-rad). The measurement procedure is described elsewhere [7, 9]. Bunch-by-bunch CBPM measurements were taken for all bunches, initially when the first bunch was excited, and then the second bunch excited and so on through the entire train. Measurements occurred for stored currents of 0.75 mA (1.1×10^{10} particles) per bunch.

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 two different values of V 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 110 and 220 sec^{-1} for the two Q_v' settings in Table 1. (These chromatic damping rates are much higher than the transverse radiation damping rate of 18 sec^{-1}.) The last column in Table 1 represents the relative excitation sent to both the H and V stripline kickers. The relative excitation is on the same scale as the excitation level for the positron data [8].

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

Scenario #	Q_s	σ_z (mm)	Q'_h	Q'_v	Relative Excitation
1787	0.025	27.3	0.6	3.1	1
1789	0.025	27.3	3.9	8.4	1
1790	0.040	17.3	0.6	3.1	1
1791	0.040	17.3	3.9	8.4	1
1792	0.050	13.6	0.6	3.1	1
1793	0.050	13.6	3.9	8.4	1
1785	0.064	10.8	0.6	3.1	1
1786	0.064	10.8	3.9	8.4	1

ANALYSIS METHOD

The turn-by-turn CBPM data for each bunch's trajectory was fit over 42 turns to free betatron and synchrotron motion [8], using the design optics between BPMs and accounting for the operating tunes by correcting the phase advance between the groups of BPMs. The fitting begins at a time T_f after the maximum displacement was achieved for the driven bunch with the 42-turn window 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 electron injection point of CESR). Examples of this fitting algorithm may be found elsewhere [7].

PRELIMINARY RESULTS

After the trajectories have been fitted, the oscillation amplitude, A, vs. time, t, was used to calculate the damping rate, α, using

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

where A_0 is the maximum amplitude (at a starting time t_0) and as t ranges through the decay time of the oscillation. The method produces a reasonable fit to the average decay rate even in the presence of a beating of the oscillation amplitude during the decay. After computing the average tunes and damping rates for all bunches during the oscillation's decay, incorrectly fit data were removed from consideration. Data excluded from further processing included 1) bunches where the automatic trajectory fitting failed, 2) bunches where the trajectory fitting succeeded, but the oscillation amplitude was too small, or 3) the automatic data acquisition system appeared to malfunction, which lead to the wrong periodicity for the excitation or under-damped oscillations. These fitting inconsistencies caused approximately 20% of the data to be removed from the results presented here.

For these sets of conditions the next step of the data analysis was to plot the tunes and damping rates were versus the excited bunch number for three bunches (the excited bunch, the first and second bunches trailing the excited bunch.) To determine whether there were systematic dynamical effects, which increased along the length of the electron trains, a linear fit for the tunes and damping rates versus bunch number was performed for the three bunches for each set of conditions. Figure 1 displays bar graphs in the H and V planes for the slope of the frequency shift per bunch for the three bunches and the eight sets of conditions. In the H and V directions, the tune shifts are relatively small (±0.015 kHz per bunch) and these are similar for the excited bunch and trailing bunches. This suggests that there are maximum tune shifts of ±0.45 kHz along the 30 bunch electron trains stored in CESR.

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.

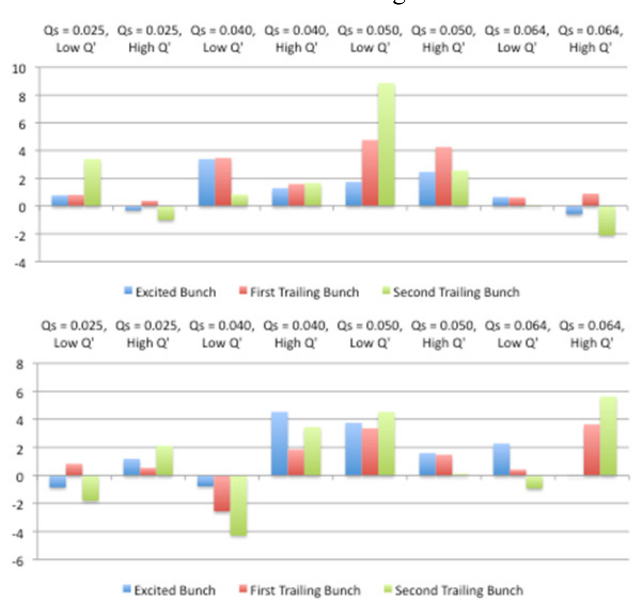

Figure 2: Bar graphs of the linear fits for the horizontal (upper) and vertical (lower) damping rates per bunch (in sec^{-1} per bunch) for the 8 sets of beam conditions for the excited bunch and first and second trailing bunches.

Figure 2 plots bar graphs for the fitted damping rate per bunch for the 8 sets of data. The slopes of the H and V damping rates per bunch range from -5 sec^{-1} to +9 sec^{-1}. The radiation damping rate for every bunch is 18 sec^{-1}, while the chromatic damping in the V plane was either 110 or 220 sec^{-1}. The entire change of the V damping rate along the 30 bunch electron train is comparable to the V chromatic damping. This implies that the change in damping along the bunch train due to dynamical effects (such as wakefields) is not particularly strong when compared to chromatic damping. There does not appear to be any significant trends for the rate of change of the damping rates vs. Q_s (bunch length) or chromaticity.

CONJECTURES BASED ON THE OBSERVATIONS

Overall coherent tune shifts and damping rates for the excited and trailing bunches for the electron bunches within trains indicate results that are comparable to single bunch dynamical effects. The point of these measurements is to compare the slopes of the coherent tunes and damping per bunch for electron bunch trains vs. positron bunch trains. The observations for the 8 sets of conditions for positron bunch trains are that the slopes are at least an order of magnitude larger than the results for electron trains in the equivalent conditions [9]. Therefore, the dynamical effects for electron trains, be they due to wake fields or the small amount of EC, are not very large, especially when compared to the dynamical effects on positron beams due to the EC.

CONCLUSIONS

This paper provides reference sets of measurements for 30 bunch electron trains to compare with 30 bunch positron trains described a companion paper [9]. The two papers have shown that ECs provide a mechanism for the damping of coherent motion as the EC density increases in the dipole-dominated storage ring, CESR.

Although there are several improvements that can be envisioned for the data acquisition process and for the processing analyses, the methods described in this paper provide an experimental mechanism for measuring the interaction of positron bunches in trains with the EC. These observations may be important for testing complete EC-beam dynamics simulations. In principle if improvements are made to the data acquisition and to the data processing, this technique may also be useful for studying multi-bunch instabilities.

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