PROGRESS IN MEASUREMENT AND MODELING OF ELECTRON CLOUD EFFECTS AT CᴇꜱʀTA

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Abstract

The synchrotron-radiation-induced buildup of low-energy electron densities in positron and proton storage rings limits performance by causing betatron tune shifts and incoherent emittance growth. The Cornell Electron Storage Ring (CESR) Test Accelerator project includes extensive measurement and modeling programs to quantify such effects and apply the knowledge gained to the design of future accelerator projects. We report on improved measurements of betatron tune shifts along a train of positron bunches, now accurate in both horizontal and vertical planes. Improved electron cloud buildup modeling uses detailed information on photoelectron production properties obtained from recently developed simulations and successfully describes the measurements after determining ring-wide secondary-yield properties of the vacuum chamber by fitting the model to data with a multi-objective optimizer. Cloud splitting in dipole magnetic fields is seen to be the source of horizontal tune shifts decreasing at higher bunch populations.

INTRODUCTION

The buildup of low-energy electrons in the vacuum chamber along a train of positron bunches can cause tune shifts, beam instabilities, and incoherent emittance growth. These electron cloud effects have been observed in many positron and proton storage rings [1], and can be a limiting factor in accelerator performance. Electron cloud effects have been observed and studied at the Cornell Electron-Positron Storage Ring (CESR) Test Accelerator (CᴇꜱʀTA) since 2008. A comprehensive summary of these studies which include electron cloud simulations, tune shift and incoherent emittance growth measurements, and mitigation methods can be found in [2]. Although these models have been successful in simulating tune shifts [3, 4] and vertical emittance growth [5] in general agreement with measurements, their predictive power is limited by the large number of free parameters. Furthermore, no single set of parameters could produce horizontal and vertical tune shifts in agreement with data at a wide range of bunch currents and beam energies. In an effort to improve the predictive power of the model for tune shifts and emittance growth, we have recently employed the Synrad3D and Geant4 codes to calculate azimuthal distributions of absorbed photons, quantum efficiencies, and photoelectron energy distributions around the vacuum chamber throughout the circumference of the CESR ring [6]. To test this model, we have measured horizontal and vertical tune shifts to greater accuracy with an improved method at a range of bunch currents.

TUNE SHIFT MEASUREMENTS

Tune shifts have been measured in a number of ways at CᴇꜱʀTA. Coherently kicking the bunch train once ("pinging") and measuring the bunch-by-bunch, turn-by-turn bunch positions yields a fast measurement of the tune shift after peak-fitting the FFTs [2, 7]. However, multiple peaks from coupled-bunch motion contaminate the signal. In addition, only vertical tune shift measurements using vertical pinger kicks are reliable with this method. The development of a vertical band of electron cloud density in dipole magnets (see next section), *i.e.,* a strong horizontal asymmetry on the scale of the beam size, is an important contribution to the tune shifts. The horizontal ping kick moves the bunch train coherently, and thus the cloud as well, so the measured horizontal tune shifts are suppressed by this measurement technique, since the test bunch receives no coherent kick from a cloud symmetric about its position. Better results are obtained by enabling bunch-by-bunch feedback on the train, and disabling it one bunch at a time and measuring the tune of that bunch. The self-excitation (no external kick applied) is enough to get a signal, but the precision can be improved by kicking the single bunch with a gated stripline kicker. In the latest measurements we improve on this technique further by utilizing a digital tune tracker which excites the bunch via a transverse kicker in a phase lock loop with a beam position monitor. The results are shown in Fig. 1. The vertical tune shift increases monotonically with bunch current. However, the horizontal tune shift shows a remarkable behavior whereby the tune shift along the train decreases with later bunches and higher currents. Our modeling shows this effect to be due to the "cloud splitting" behavior in dipoles where the vertical stripe of cloud splits into two stripes due to cloud electron energies surpassing the peak energy of the SEY curve due to the greater kicks from higher bunch populations.

SIMULATIONS

The EC buildup simulation is based on extensions [7] to the ECLOUD [8] code. Previous results used analytic forms for the distribution of synchrotron radiation in the horizontal plane of the beam, and did not take into account photon reflections. Furthermore, the azimuthal distribution of primary photoelectrons in ECLOUD was specified by a narrow Gaussian on the outside wall plus a uniform distribution elsewhere as an approximation to the contribution by reflected photons. When switching to the 3D photon tracking code Synrad3D which also includes specular and diffuse reflections, we obtain an azimuthal distribution of absorbed photons which is dramatically different. Furthermore, quan-
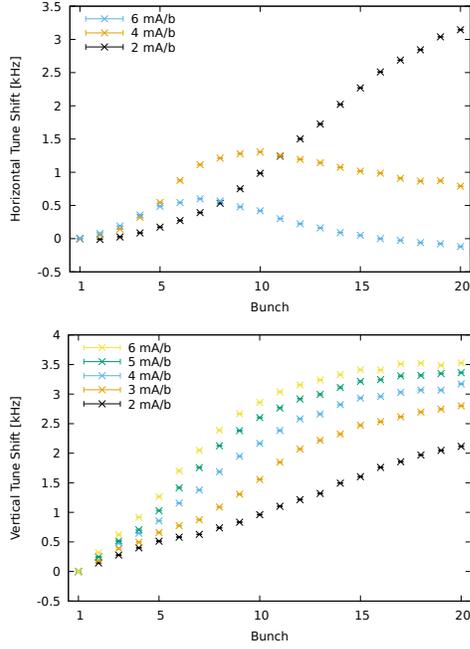
Figure 1: Horizontal (top) and vertical (bottom) tune shift in kHz (to be compared to the revolution frequency of 390 kHz) for a 20 bunch trains of positrons between 2–6 mA/b (3.2–9.6×10^{10} bunch populations). Data were taken in each plane separately, and only at 2, 4, and 6 mA/b in the horizontal plane.
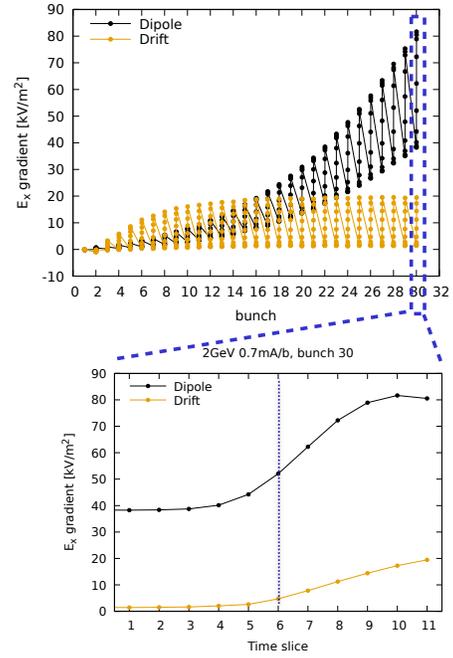

Figure 2: Top: horizontal electron cloud space-charge electric field gradients for the 11 time slices within each of 30 bunches, for dipoles and drifts. Bottom: electric field gradients for the 11 time slices in bunch 30, showing the center of the bunch at time slice 6.

tum efficiencies are calculated with a Geant4 simulation in -0.5-degree azimuthal bins, averaged over field-free and dipole regions of the ring separately. These photoelectron production rates also have a large azimuthal dependence due to the strong dependence on absorbed photon energies and their incident angles (see [6]). Additionally the photoelectron energy distributions are calculated as a function of azimuth, exhibiting a strong, fine-grained dependence. The result is the replacement of unknown or nonphysical parameters with detailed distributions from simulations, which take into account the effects of different beam energies and vacuum chamber materials and conditions, to extend the range of validity of the model and its predictive power.

The modeled tune shifts are calculated from the cloud space-charge electric field gradients. ECLOUD simulations are performed recalculating the space-charge field in 11 time slices during each bunch passage. The "pinch effect", wherein the bunch attracts the nearby cloud as it passes, can be clearly seen in Figs. 2 and 3 as a dramatic increase in electric field gradients.

However, since the bunch length is a mere 16 mm long, it hardly perturbs the built-up cloud during its passage. Additionally, for an offset bunch (the one being excited) in an on-axis train, the pinched cloud is found to be centered on the offset bunch, even in the presence of a dipole field (shown in Fig. 4). Thus the kick on the offset bunch due to the pinched cloud can be neglected, and therefore does not contribute to the coherent tune shift. The pinched cloud can

however contribute to incoherent tune spread and emittance growth [5]. For this reason, the space-charge electric field gradients just prior to the bunch arrival (and pinch effect) are used when calculating the tune shifts.

RESULTS

We have developed a multi-objective optimizer which adapts a chosen set of ECLOUD input parameters to the complete set of measurements, including horizontal and vertical tune shifts measured for 5.3 GeV positrons along 20-bunch trains with bunch populations varying from 3.2–9.6×10^{10}. In order to improve agreement with the comprehensive data set, a systematic method of fitting these parameters was required. At each iteration, simulations are run in parallel with each parameter varied by an adaptive increment. Then the Jacobian is calculated and fed into the optimizer. The modeled tune shifts are quite sensitive to a variety of SEY parameters in correlated ways. Previous measurements of SEY parameters provide an acceptable starting point for the parameters, but many have not been determined to our required accuracy, or have been obtained under conditions or measurement methods which differ from our case, where we are using CESR-ring-wide averages. The results are shown in Fig. 5 where the optimized input parameters are: peak energy of the true secondary yield, true secondary SEY shape parameter s, rediffused secondary yield, true secondary yield, and elastic yield at zero energy [9]. Further optimization studies are being actively pursued.
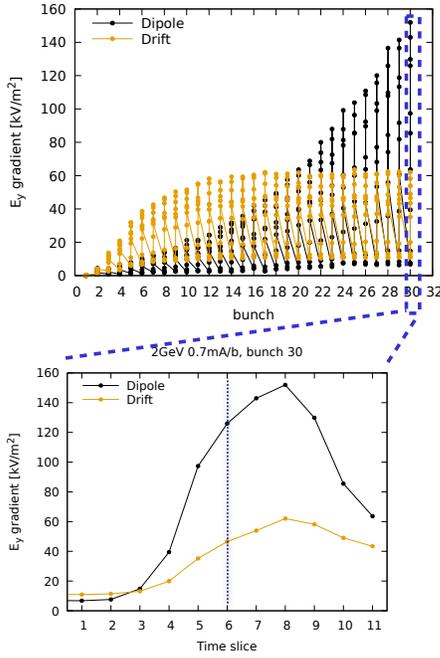
Figure 3: Top: vertical electron cloud space-charge electric field gradients for the 11 time slices within each of 30 bunches, for dipoles and drifts. Bottom: electric field gradients for the 11 time slices in bunch 30, showing the center of the bunch at time slice 6.

SUMMARY

We have obtained improved measurements of betatron tune shifts along trains of positron bunches in the horizontal and vertical planes for a range of bunch populations, enabling advances in the predictive power of electron cloud buildup modeling. We employed the Synrad3D and Geant4 simulation codes to eliminate ad hoc assumptions in photo-electron production rates and kinematics characteristic of prior buildup simulations (see [6] for details). Electron cloud model parameters for secondary electron yield processes were determined through tune shift modeling calculations optimized to the measurements. This work achieves for the first time agreement between simulated tune shifts and the measurements in both horizontal and vertical planes over a broad range in bunch population, identifying quantitatively the cloud splitting effect in dipole magnetic fields. Extension to tune shift measurements at 2.1 GeV beam energy is underway, as is the study of electron cloud as the source of incoherent vertical emittance growth.
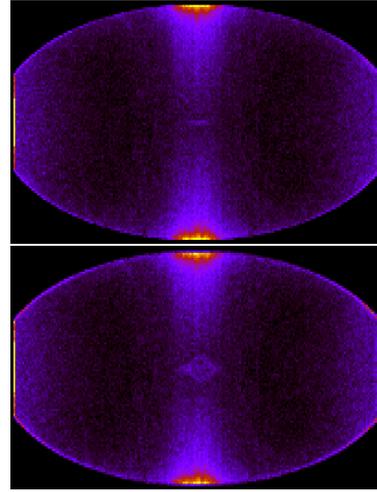
ACKNOWLEDGMENTS

Figure 4: Simulated electron cloud density during the 3rd (top) and 6th (bottom) of 11 time slices during of the passage of bunch 15 (arbitrary), which has been offset from the centered bunch train by 1 mm horizontally to simulate the effect of kicking a single bunch when measuring its tune. The "pinched" cloud is found to be centered on the offset bunch position. The short bunch length (16 mm) bunch hardly modifies the larger built-up cloud. The simulated bunch current is 2 mA/b. At higher currents, the vertical band widens (4 mA/b) and splits into two (6 mA/b).
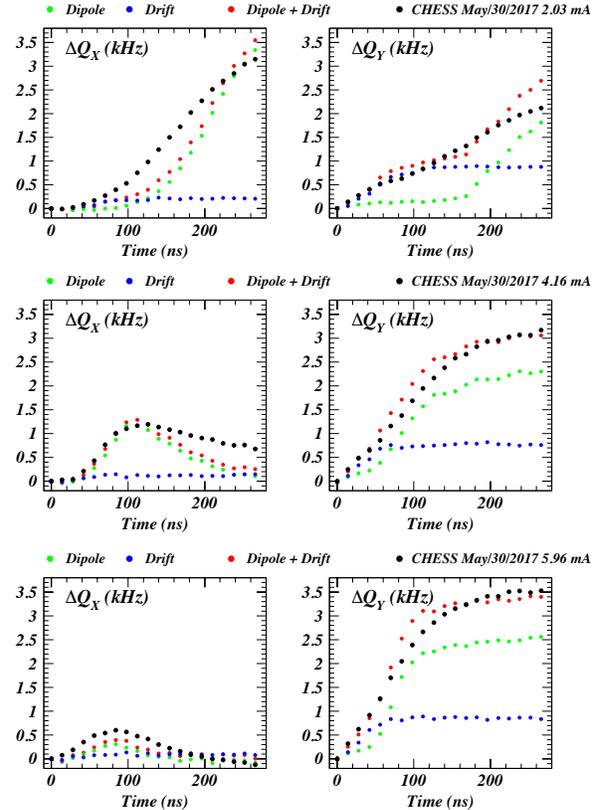

Figure 5: Horizontal (left) and vertical (right) tune shifts from data (black) and simulations (red: sum of dipoles (green) and drifts (blue)) for 20 bunch trains of positrons at 2, 4, and 6 mA/b.

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