Studies of the Effects of Electron Cloud Formation on Beam Dynamics at CesrTA

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Abstract

The Cornell Electron Storage Ring Test Accelerator (CesrTA) has commenced operation as a linear collider damping ring test bed following its conversion from an e^+e^--collider in 2008. A core component of the research program is the measurement of effects of synchrotron-radiation-induced electron cloud formation on beam dynamics. We have studied the interaction of the beam with the cloud with measurements of coherent tune shifts and emittance growth in various bunch train configurations, bunch currents, beam energies, and bunch lengths, for both e^+ and e^- beams. This paper compares a subset of these measurements to modeling results from the two-dimensional cloud simulation packages ECLOUD and POSINST. These codes each model most of the tune shift measurements with remarkable accuracy, while some comparisons merit further investigation.

INTRODUCTION

Investigations of beam dynamics effects associated with electron cloud buildup began at CESR in 2007, prior to the conversion of the storage ring to the CesrTA configuration [1] in November, 2008. In April, 2007, bunch-by-bunch measurements of coherent tune shifts showed them to increase along a 10-bunch train and to be of opposite sign for the 1.9 GeV electron and positron beams, providing an early indication of electron cloud formation. Further data sets were obtained during runs at 5.3 GeV in June, 2008, and at 2.1 GeV in January, 2009. In addition to the coherent tune shift measurements, preliminary investigations of emittance growth arising from electron-cloud-induced instabilities have been performed and will continue this summer [2]. This report concentrates on the substantial progress made in understanding the coherent tune shifts caused by electron cloud buildup.

COHERENT TUNE MEASUREMENT

The coherent tune shifts are determined by kicking the beam with a magnetic pulsed element and performing an FFT analysis on the bunch-resolving beam position monitor measurements of the damped orbit oscillations during 1024 revolutions (2.6 ms). An estimate of the uncertainty in the calculated tune shifts is obtained by immediately repeating the measurement several times. A systematic study into the dependence of the tune measurement on the magnitude of the pulsed magnetic kick showed negligible effect when the kick was lowered by a factor of two and raised by 50%. The peak orbit oscillation amplitude for the measurements considered here is about 2 mm.

SIMULATIONS

The electron cloud buildup simulation code packages POSINST and ECLOUD were employed to study the physics phenomena contributing to the tune shift mechanism. A description of these algorithms can be found in Ref. [3]. We performed systematic comparisons of the results from these packages [4], one consequence of which was to replace the angular distribution of primary photoelectrons in ECLOUD with that used in POSINST. Calculations of the synchrotron radiation (s.r.) flux based on the lattice optics were used to determine the photon-per-beam-

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particle rate averaged for all drift (dipole) regions of the ring, which comprises 23% (62%) of the ring circumference. The contribution to the tune shift from the remaining 15% of the ring, comprised primarily of quadrupoles, was ignored. While these s.r. rate values are well-determined from the optics, the quantum efficiency for producing photoelectrons is not well known. Our chosen value of 12% for the quantum efficiency gives reasonable agreement with the tune measurements. Another poorly known input parameter is the value for the photon reflectivity, which subtracts a fraction of the primary photoelectron yield from the primary source point in the horizontal plane and distributes it around the 4.5 cm *x* 2.5 cm elliptical beampipe in the transverse plane. For the present study the distribution is uniform. The reflectivity largely determines the dipole contribution, since the cloud particles are pinned to the vertical field lines, affecting the beam only when source points exist in the vertical plane intersecting the beam. An effective value for the reflectivity is well constrained by the measurements, since the time dependence of the cloud buildup in drifts and dipoles is very different. We use a reflectivity value of 15%.

The secondary electron yield model in POSINST is described in detail in Ref. [5]. At low incident electron energy, an elastic production mechanism dominates, while the production of “true secondaries” dominates for incident energies above a few eV. The energy dependence of the true secondary yield is parameterized similarly in ECLOUD and POSINST, determined by the values for the secondary charge yield per incident charge and the incident energy at peak yield. We used values of 2.0 and 310 eV, which are reasonable choices for the processed aluminum vacuum chamber. A study of the modeled tune dependence on these input parameters showed the measurements to effectively constrain their values, but cannot exclude other combinations, such as 1.2 and 170 eV. It is expected that data with varying bunch current will help to distinguish the two, since the high energy spectrum of the cloud is determined by beam kicks. Just as the variation measurement parameters allow us to explore the range of relevant physics phenomena, so, too, do the differing secondary-emission models in ECLOUD and POSINT instruct us in the varying sensitivity to those subprocesses.

Initially we derived tune shift values from the calculated space-charge field gradients averaged over the beam profile at the center of the pipe, folded with drift- and dipole-averaged beta function values. These gave fair agreement with the time dependence of the tune shifts, but failed to produce the dominance of the vertical tune shift over the horizontal tune shift which are a general feature of the CesrTA data. Gauss’s law ensures the sum of horizontal and vertical tune shifts to be equal and opposite in the absence of any charge in the beam region when the horizontal and vertical beta functions are equal. Since the average beta functions in each plane for both drift and dipole regions are similar at the 20% level, the tune shifts are apparently particularly sensitive to the cloud near the beam. Also, our use of the field gradients ignored dynamical effects associated with the oscillation of the beam. The pulsed magnetic kick used for the tune shift measurements affected all bunches coherently in the data sets considered here. We found it important to include this coherent oscillation of all bunches in modeling the development of the cloud. We calculate the field averaged over the bunch profile $\langle E\rangle_{\pm x,y}$ for beams offset by amounts $\Delta x, y$ characteristic of the 2 mm peak oscillation, and use the linear dependence $(\langle E\rangle_{+x,y} - \langle E\rangle_{-x,y})/\Delta x, y$ to calculate the modeled tune shifts. This computation accounts for the coherent motion of the cloud in response to the magnetic-kick-induced oscillations of the beam. The modeled horizontal tune shifts are consequently greatly reduced in dipole regions owing to field pinning.

RESULTS

Figure 1 shows the measurements and modeling results for the data taken in 2007 with e^+- and e^--beams in the 1.885 GeV lattice. Both data and simulation runs were performed with bunch configurations comprising a 10-bunch cloud-initiating train followed at various intervals (increments of the 14-ns bunch spacing) by a witness bunch sensitive to the space-charge field of the cloud as it decayed. Both the initiating train bunches and the witness bunches carried 0.75 mA (1.2×10^{10} e) to within a few percent. The kHz-level tune shifts are to be compared to the 390 kHz revolution frequency. POSINST I uses an analytic formula for the electric field averaged over the transverse bunch charge profile (including image charge effects) due to a line

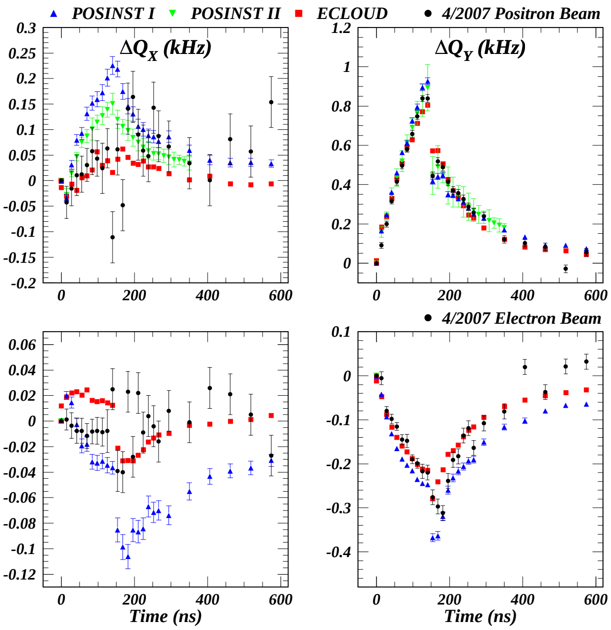

Figure 1: Comparison of the tune measurements to modeling results for the 1.885 GeV electron and positron data recorded in 2007

charge element of the cloud, sums this over all the macro-electrons in the cloud, and averages over the longitudinal bunch charge profile. Since these 2D fields have no longitudinal dependence, the longitudinal average is simply a Gaussian integral. POSINST II obtains the bunch-charge-averaged electric field instead from a numerical solution to the 2D Poisson equation. ECLOUD clusters the cloud charges on the nodes of a 4.5 cm *x* 2.5 cm, 41 *x* 41 rectangular grid and obtains the electric field from a sum over these charges and their images. This approximation was checked by comparison to the results of a non-clustered (much slower) calculation. The POSINST I calculations derive uncertainty values based on cloud macro-electron statistics, while the POSINST II error bars represent 3σ values for the uncertainty in the linear coefficent of the fit to the calculated field versus beam offset for the ten beam offsets used. No attempt to determine error bars has yet been made for the ECLOUD calculations. All simulations assumed a value of 0.23 (0.53) photons per beam particle per meter for the average s.r. photon rate in the drift (dipole) regions. While the magnitude and time dependence of the tune shifts are well reproduced by the three simulations, significant differences can be seen for the witness bunches following closely after the 10-bunch train, when the beam kicks first stop contributing to the cloud charge motion. Also, not shown here, the ECLOUD calculations indicate that most of the positron (electron) beam vertical tune shift occurs in drift (dipole) regions during buildup, while POSINST results indicate very similar contributions from the two regions.

Figure 2 shows witness bunch data recorded in 2008 prior to the CesrTA reconfiguration. The optics were those used for operation as a X-ray light source at 5.3 GeV. The bunch current was again 0.75 mA for all bunches. Modeling parameters were chosen as for the 2007 data with the exception of the s.r. fluxes, which were approximately doubled. These results clearly show nonlinear effects in the relationship between the cloud buildup and decay which should permit fine-tuning of the secondary yield model.

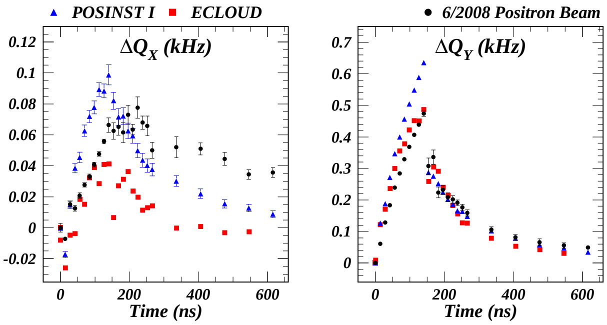

Figure 2: Comparison of the tune measurements to modeling results for the 5.3 GeV positron data recorded in 2008

Figure 3 shows results for 45-bunch train tune shift measurements recorded in January, 2009 in the CesrTA configuration [1]. The bunch current was again 0.75 mA. Such long trains are particularly interesting for distinguishing the drift and dipole contributions to the tune shifts, since the drift contribution saturates after about 15 bunches, increasing by less than 10% thereafter, while the dipole contribution continues to grow. The dipole tracking model in ECLOUD remains under investigation. Here we use the simplified option of an infinitely strong dipole field, which gives results similar to the Runge-Kutte tracking used for the 2007 and 2008 data.

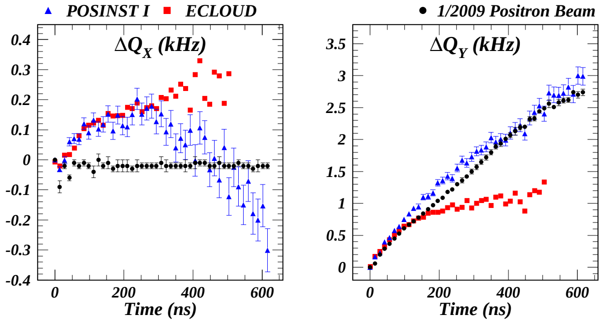

Figure 3: Comparison of the tune measurements to modeling results for the 2.1 GeV positron data recorded in 2009

FUTURE PLANS

The CesrTA project is presently concentrating an intense effort on instrumentation upgrades [7]. CesrTA measurement periods are scheduled for three weeks in June and four weeks in October. The coherent tune shift measurements will be extended to various bunch configurations, including 4-ns spacing, and various bunch currents and beam emittance. Coherent emittance growth experiments are planned for this summer, as are investigations of electron-cloud-induced head-tail instabilities.

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