SLAC-PUB-15763

# STUDIES AT CESRTA OF ELECTRON-CLOUD-INDUCED BEAM DYNAMICS FOR FUTURE DAMPING RINGS *

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*Abstract*

Electron clouds can adversely affect the performance of accelerators, and are of particular concern for the design of future low emittance damping rings. Studies of the impact of electron clouds on the dynamics of bunch trains in Cesr have been a major focus of the Cesr Test Accelerator (CesrTA) program. In this paper, we report measurements of coherent tune shifts, emittance growth, and coherent instabilities carried out using a variety of bunch currents, train configurations, beam energies and transverse emittances, similar to the design values for the ILC damping rings. The measurements will be compared with simulations which model the effects of electron clouds on beam dynamics, to extract simulation model parameters and to quantify the validity of the simulation codes.

## INTRODUCTION

In this paper, we will describe some of the recent experimental measurements [1, 2] performed at CesrTA [3], and the supporting simulations, which probe the interaction of the electron cloud with the stored beam. These experiments have been done over a wide range of beam energies, emittances, bunch currents, and fill patterns, to gather sufficient information to be able to fully characterize the beam-electron-cloud interaction and validate the simulation programs. The beam conditions are chosen to be as close as possible to those of the ILC damping rings, so that the validated simulation programs can be used to predict the performance of these rings with regard to electron-cloud-related phenomena.

## EXPERIMENTAL HARDWARE AND TECHNIQUES

The principal experimental methods [4, 5, 6] used to study the dynamics of the beam in the presence of the electron cloud are:

- bunch-by-bunch tune measurements using one or more gated BPM's, in which a whole train of bunches is coherently excited, or in which individual bunches are excited;
- bunch-by-bunch frequency spectral measurements of self-excited bunch trains, using a high-sensitivity, filtered and gated BPM, and a spectrum analyzer;
- damping time measurements of individual bunches in trains excited in dipole and head-tail modes, using a high-sensitivity, filtered and gated BPM, a spectrum analyzer, a transverse kicker and an RF-cavity phase modulator; and
- bunch-by-bunch, turn-by-turn beam size measurements of self-excited bunch trains, using an x-ray beam size monitor [6].

* Work supported by the US National Science Foundation (PHY-0734867, PHY-1002467, and PHY-1068662), US Department of Energy (DE-FC02-08ER41538), and the Japan/US Cooperation Program

## COHERENT TUNE MEASUREMENTS

A large variety of coherent tune shift data have been taken, covering a wide range of beam and machine conditions. The contribution to the bunch-by-bunch tune shifts from drift and dipole beamline elements have been computed from the electric field gradients of the charge distributions predicted by the electron cloud simulation codes. The ringwide average tune shifts were then calculated by taking a beta-weighted average of the tune shifts per beamline element, and compared with measurements.

Quite good agreement [7, 8, 9, 10] has been found between the measurements and the computed tune shifts, using either of the buildup codes POSINST [11] or ECLOUD [12]. This agreement, which is found for the same set of simulation parameters applied across a wide variety of machine conditions, both constrains many of the model parameters and gives confidence that the models do in fact predict accurately the average density of the electron cloud measured in CesrTA.

To help characterize the photoelectrons which seed the cloud in CesrTA, and to allow accurate extrapolation to other radiation environments, a new simulation program, SYNRAD3D [13], has been developed, which predicts the distribution and energy of absorbed synchrotron radiation photons around the ring, including specular and diffuse scattering in three dimensions, for a realistic vacuum chamber geometry. The output from this program can be used as

*Presented at the 3rd International Particle Accelerator Conference (IPAC 2012)*
*New Orleans, Louisiana, USA, May 20 - 25, 2012*

*Work supported in part by US Department of Energy under contract DE-AC02-76SF00515.*

input to the cloud buildup codes, thereby eliminating the need for any ad-hoc assumptions in these codes about the photon distributions. Tune shifts computed from buildup simulations with input from SYNRAD3D agree well with measurements (see Fig. 1).

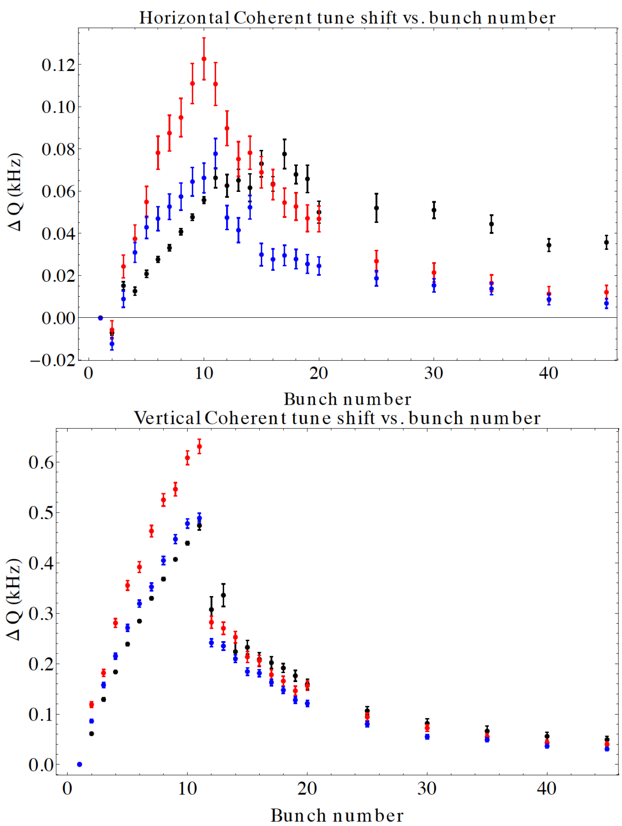


Figure 1: Measured tune shifts (black points) vs. bunch number, for a train of 10 0.75 mA/bunch 5.3 GeV positron bunches with 14 ns spacing, followed by witness bunches. Red points are computed (using POSINST) based on direct radiation and an ad-hoc assumption about the scattered photons. Blue points are computed using results from SYNRAD3D as input to POSINST.

## INSTABILITY THRESHOLD MEASUREMENTS

Using a high-sensitivity, filtered and gated BPM, and a spectrum analyzer, bunch-by-bunch frequency spectra have been collected for a variety of machine and beam conditions, to detect signals of single-bunch instabilities which develop along trains of positron bunches. Under conditions in which the beam is self-excited via the electron cloud, these frequency spectra exhibit the vertical $m = \pm 1$ head-tail (HT) lines, separated from the vertical betatron line by approximately the synchrotron frequency, for many of the bunches along the train. The amplitude of these lines typically (but not always) grows along the train. Two examples of how the power in these lines varies along the train are shown in Fig. 2.

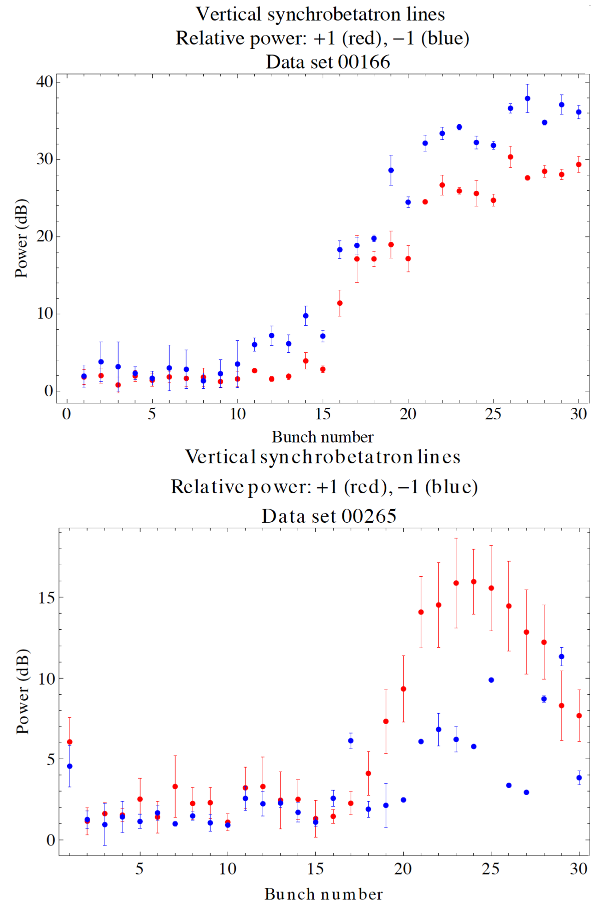


Figure 2: Vertical head tail lines, peak power vs. bunch number. Top: Data set 166: 2.1 GeV. Chromaticity: (H,V) = (1.33, 1.16). Bunch current = 0.74 mA. Bottom: Data set 265: 4 GeV. Chromaticity: (H,V) = (1.3, 1.4). Bunch current = 1.1 mA.

By measuring the coherent tune shifts along the train at the same time, the electron cloud density can be determined directly from the tune shifts using the approximate relation

$$\langle \rho_c \rangle = \gamma \frac{\Delta Q_x + \Delta Q_y}{r_e \langle \beta \rangle C},$$

in which $\langle \beta \rangle$ is the average beta function, $C$ is the ring circumference, $\gamma$ is the beam Lorentz factor, and $r_e$ is the classical electron radius. Alternatively, the corresponding density can be obtained from a simulation which is adjusted to predict the measured tune shifts. An example for the conditions of data set 166 is shown in Fig. 3.

By comparing this figure with the top plot in Fig. 2, we can conclude that the onset of the HT lines occurs at a ring-wide initial (i.e., before the "pinch") beam-averaged cloud density of around $8 \times 10^{11}$ $\mathrm{m}^{-3}$ for 2.1 GeV beam energy. Using this same method, the corresponding threshold density at 4 GeV was determined to be about $2 \times 10^{12}$ $\mathrm{m}^{-3}$.

Other observations from systematic studies are:

- The betatron lines exhibit structure which varies along the train. The vertical line power grows along the train

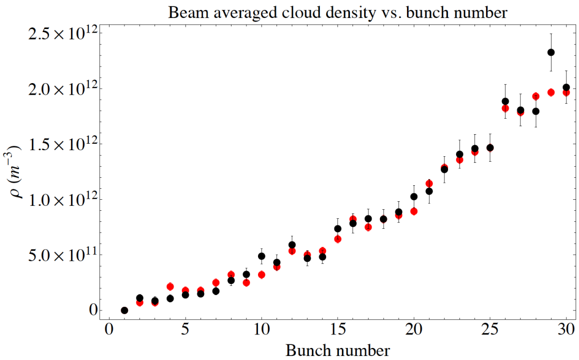


Figure 3: Data set 166: Average initial (i.e., before the "pinch") electron cloud density vs. bunch number, comparison between estimate from measured tune shifts (red), and simulation (black) from `POSINST`.

and has a fine structure that is not understood.

- The onset of the HT lines depends strongly on the vertical chromaticity, the beam current and the number of bunches
- For a 45 bunch train, the HT lines have a maximum power around bunch 30; the line power is reduced for later bunches.
- There is a weak dependence of the onset of the HT lines on the synchrotron tune, the single-bunch vertical emittance, and the vertical feedback.
- Under identical conditions, HT lines also appear in electron trains, but the onset is later in the train, develops more slowly, and is much weaker, than for positrons.
- Under some conditions, the first bunch in the train also exhibits a head-tail line ($m = -1$ only). The presence of a "precursor" bunch can eliminate the $m = -1$ signal in the first bunch. The implication is that there may be a significant "trapped" cloud density near the beam which lasts long after the bunch train has ended, and which is dispersed by the precursor bunch. Indications from RFA measurements and simulations indicate this "trapped" cloud may be in the quadrupoles [15] and wigglers [14].
- The HT line structure observed for the last bunch in a 30 bunch train varies strongly as a function of the current in that bunch. But the frequency of the vertical betatron line of this bunch is only very weakly dependent on the current in the bunch.

## MODE GROWTH RATE MEASUREMENTS

To measure the damping or anti-damping effects attributable to the electron cloud, we have made measurements in which we actively excite a single bunch in a train, and measure the rate at which the bunch damps after the excitation is turned off. These bunch-by-bunch damping rate measurements can be made for the $m = 0$ (dipole mode) of motion, and for the $m = \pm 1$ (head tail modes).

To date, measurements of bunch-by-bunch damping rates have only been made for two sets of conditions. Generally, the damping rate for motion of bunches in the train lessens as the electron cloud builds up. The vertical dipole and head-tail modes become unstable at approximately the same bunch within the train, although the data is suggestive of the head-tail modes becoming unstable at a slightly earlier bunch than when the dipole mode destabilizes. An example is shown in Fig. 4.

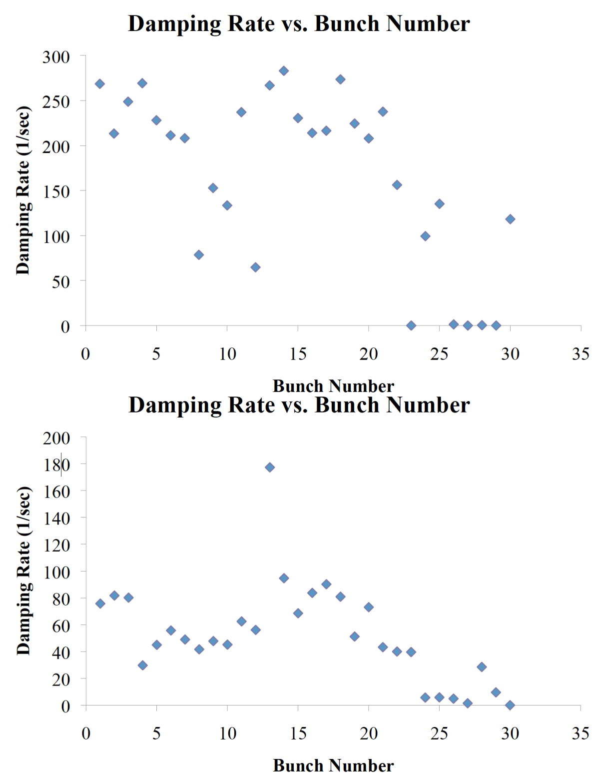


Figure 4: Vertical damping rate vs. the bunch number of a 30-bunch-long train of positrons at 2.1 GeV. Chromaticity: (H, V) =(0.58, 2.13) and the vertical feedback setting is 20% of full scale. Top: $m = 0$ mode. Bunch current = 0.72 mA; estimated single bunch damping rate of 200 $s^{-1}$. Bottom: $m = -1$ head-tail mode. Bunch current = 0.75 mA; estimated single bunch damping rate of 110 $s^{-1}$.

## MEASUREMENTS OF EMITTANCE GROWTH ALONG BUNCH TRAINS

Using an x-ray monitor [6], bunch-by-bunch beam position and size measurements have been made on a turn-by-turn basis for positron beams. From the beam size measurements, the evolution of the beam emittance along trains of bunches has been measured.

Beam centroid motion and vertical emittance are observed to grow along the train. The growth pattern is a strong function of the bunch current (see Fig. 5). Often, the first bunch in the train has an anomalously large size, which correlates with of the observation of a vertical head-tail line in the spectrum of this bunch, as discussed above.

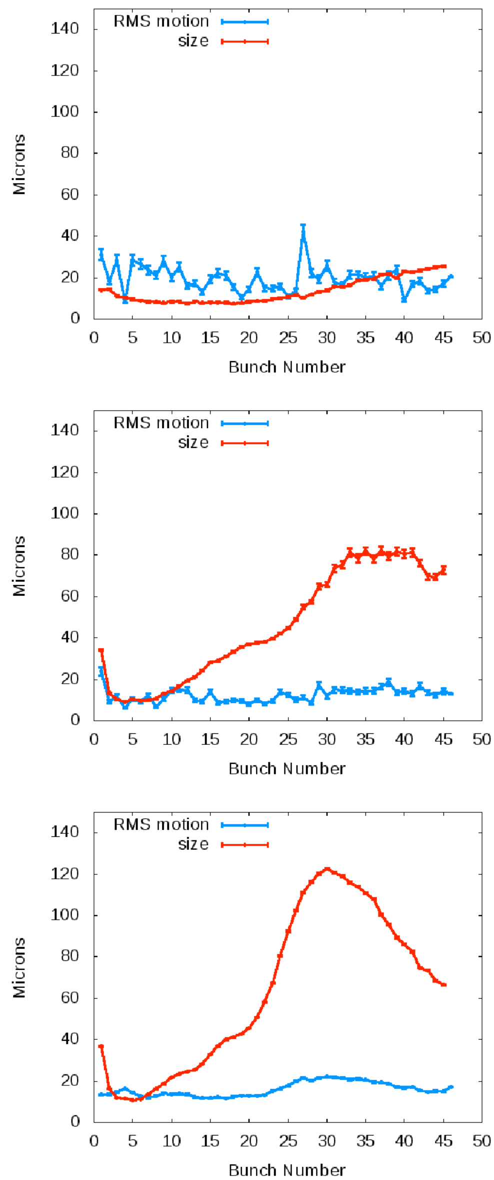


Figure 5: Bunch-by-bunch beam size and rms motion at 14 ns spacing and 2.1 GeV. Top: bunch current 0.5 mA/bunch (128 turns). Center: bunch current 1 mA/bunch (4096 turns). Bottom: Bunch current 1.3 mA/bunch (4096 turns).

In Fig. 6, the bunch-by-bunch beam size and rms motion are shown for a measurement with a 14 ns train, at 4 GeV, with 1.1 mA/bunch. The conditions for this measurement are exactly the same as those for the bunch-by-bunch frequency measurement whose head-tail line growth is shown in the bottom plot of Fig. 2. The $m = 1$ vertical head-tail line starts growing at bunch 18 and peaks around bunch 22. Comparing with Fig. 6, the vertical emittance growth starts at bunch 17 and reaches a plateau around bunch 22. Thus the onset and development along the train of the vertical head-tail line is very similar to the onset and development along the train of vertical emittance growth. This is what one would expect if the vertical emittance growth was driven by coherent head-tail motion.

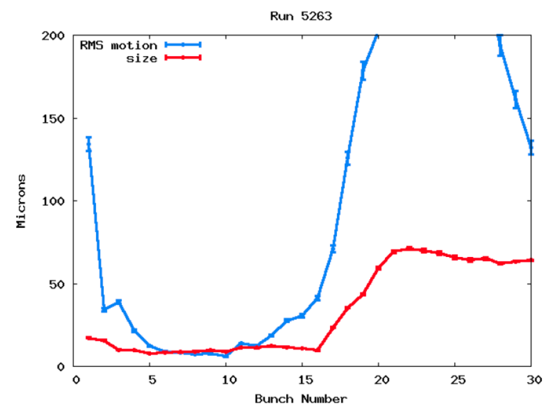


Figure 6: Bunch-by-bunch beam size and rms motion at 14 ns, 4 GeV, with 1.1 mA/bunch.

Other key observations are:

- The threshold for beam size growth along the train is not very sensitive to the chromaticity or the bunch spacing, although the maximum beam size along the train is larger for a smaller chromaticity. This dependence on the chromaticity is in contrast to the behavior of the head-tail lines, which are quite sensitive to chromaticity.
- Beam size growth along the train is also not very sensitive to the initial beam size or the feedback gain.

## COMPARISONS WITH ANALYTIC ESTIMATES AND SIMULATIONS

The analytic theory discussed in [17] was used to estimate the head-tail instability threshold in the coasting beam approximation. At 2.1 GeV, the analytical estimate of the threshold density is $1.3 \times 10^{12}$ m$^{-3}$, about 60% higher than the measured threshold of $8 \times 10^{11}$ m$^{-3}$. At 4 GeV, the analytical estimate of the threshold density is $2.65 \times 10^{12}$ m$^{-3}$, about 30% higher than the measured threshold of $2 \times 10^{12}$ m$^{-3}$.

Numerical simulations using PEHTS [16] have been done to refine the estimates of the threshold density at both 2 and 5 GeV. These simulations [17] show both vertical emittance growth, and the presence of head-tail lines in the beam's dipole motion spectrum, above the threshold density. The simulations show that dipole feedback is not able to suppress the emittance growth. The effects of dispersion, and a realistic lattice with 83 beam-cloud interaction points, were also studied. The threshold densities found for the realistic lattice (about $1.2 \times 10^{12}$ m$^{-3}$, see Fig. 7, top) were about 50% higher than the analytical estimates (for the same beam parameters).

Numerical simulations using CMAD [18] were also done for 2 GeV beam energy. These simulations use a realistic lattice, with beam-cloud interaction points at every lattice element. As with PEHTS, they show both vertical emittance growth, and the presence of head-tail lines in the beam's dipole motion spectrum. For the same cloud density above the head-tail threshold, CMAD and PEHTS predict the same level of vertical emittance growth after 500 turns, within a factor of 2 (see Fig. 7).

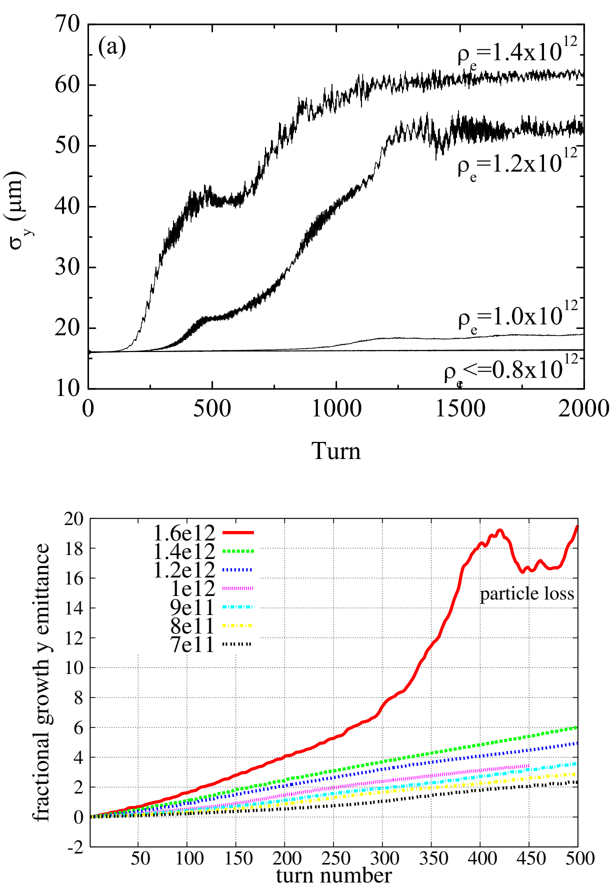


Figure 7: Evolution of the beam size at 2 GeV, using realistic lattices. Top: PEHTS simulation [17]. Bottom: CMAD simulation

For the realistic lattice, PEHTS was also used to estimate incoherent emittance growth below the head-tail threshold. At an electron-cloud density of $0.8 \times 10^{12}$ $m^{-3}$ in the 2 GeV case, the beam size growth rate is about $7.4 \times 10^{-6}$ $\sigma_y$/turn. While this is less than the radiation damping rate of $4.6 \times 10^{-5}\sigma_y$/turn, it could still result in some modest ($\sim 20\%$) growth in the equilibrium vertical emittance. Experimental studies to look for such emittance growth are planned for the future.

## REFERENCES

[1] M. G. Billing, *et. al.*, "Status of Electron Cloud Dynamics Measurements at CESRTA", IPAC11, San Sebastian, Spain, 2011, MOPS084, p. 799-801.

[2] G. Dugan, *et. al.*, "Studies of Electron-Cloud-Induced Beam Dynamics at CesrTA", ECLOUD'10, Ithaca, NY, DYN03.

[3] M. A. Palmer, *et. al.*, "The Conversion and Operation of the Cornell Electron Storage Ring as a Test Accelerator (CesrTA) for Damping Rings Research and Development", PAC09, Vancouver, BC, 2009, FR1RAI02, p. 4200-4204.

[4] M. G. Billing, *et. al.*, "Measurement Techniques to Characterize Instabilities Caused by Electron Clouds", PAC11, New York, NY, 2011, WEP194, p. 1852-1854.

[5] M. G. Billing, *et. al.*, "Techniques for Observation of Beam Dynamics in the Presence of an Electron Cloud", IPAC10, Kyoto, Japan, 2010, MOPE091, p. 1197-1199.

[6] N. T. Rider, *et. al.*, "Development of an X-Ray Beam Size Monitor with Single Pass Measurement Capability for CesrTA", PAC11, New York, NY, 2011, MOP304, p. 687-689.

[7] D. L. Kreinick, *et. al.*, "Application of Coherent Tune Shift Measurements to the Characterization of Electron Cloud Growth ", PAC11, New York, NY, 2011, WEP108, p. 1680-1682.

[8] D. L. Kreinick, *et. al.*, "Using Coherent Tune Shifts to Evaluate Electron Cloud Effects on Beam Dynamics at CesrTA", ECLOUD'10, Ithaca, NY, PST10.

[9] J. A. Crittenden, *et. al.*, "Progress in Studies of Electron-cloud-induced Optics Distortions at CesrTA", IPAC10, Kyoto, Japan, 2010, TUPD024, p. 1976-1978.

[10] J. A. Crittenden, *et. al.*, "Studies of the Effects of Electron Cloud Formation on Beam Dynamics at CesrTA", PAC09, Vancouver, BC, 2009, FR5RFP044, p. 4631-4633.

[11] M. A. Furman, G. R. Lambertson, Proc. MBI-97, KEK Proceedings 97-17, p. 170; M. A. Furman, M. T. F. Pivi, PRST-AB 5, 124404 (2002).

[12] D. Schulte, F. Zimmermann, "Electron Cloud Build-Up Simulations using ECLOUD", ECLOUD'04, Napa, CA, p. 143-152; G. Rumolo, F. Zimmermann, "Electron Cloud Simulations: Beam Instabilities and Wake-fields", Phys. Rev. ST Accel. Beams 5, 121002 (Dec. 2002).

[13] G. Dugan, D. Sagan, "Synrad3D Photon Propagation and Scattering Simulation", ECLOUD'10, Ithaca, NY, PST08.

[14] C. M. Celata, "Electron Cloud Dynamics in the Cornell Electron Storage Ring Test Accelerator Wiggler", Phys. Rev. ST Accel. Beams 14, April 2011, 041003.

[15] L. Wang, M. Pivi, "Trapping of Electron Cloud in ILC/CesrTA Quadrupole and Sextupole Magnets", ECLOUD'10, Ithaca, NY, MOD05

[16] K. Ohmi, "Particle-in-Cell Simulation of Beam-Electron Cloud Interactions", PAC01, Chicago, IL, P. Lucas & S. Webber, Eds. (2001), p. 1895-1897.

[17] H. Jin, *et. al.*, "Electron Cloud Effects in Cornell Electron Storage Ring Test Accelerator and International Linear Collider Damping Ring", Jpn. J. Appl. Phys. 50, February 2011, 026401.

[18] M. T. F. Pivi, "CMAD: A New Self-consistent Parallel Code to Simulate the Electron Cloud Build-up and Instabilities", PAC07, Albuquerque, NM, 2007, THPAS066, pp. 3636-3638