Studying Beam Dynamics at CesrTA

A Senior Project

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Bachelor of Science

by

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Abstract

The Cornell Electron Storage Ring Test Accelerator (CesrTA) is a particle accelerator acting primarily as a laboratory for studying accelerator physics under a variety of conditions. Here, the experimental program on electron cloud effects is one of the highest-priority research and development projects during the International Linear Collider (ILC) Technical Design Phase 1[1]. These electron clouds are of particular concern for the design of future low emittance rings like those in the ILC because of how they can adversely affect the performance of accelerators. The impact of electron clouds on the dynamics of individual bunches along a train known as the tune indicate the magnitude of electron cloud growth within the accelerator. This paper provides explanation as to how these electron clouds are created, how they affect beam dynamics, as well as the techniques for calculating tune shifts for observing this phenomenon.

Introduction

Theory

Ironically enough, particle accelerators are some of the largest and most powerful machines ever constructed, yet are focused on studying the smallest things in the universe. Particle physicists use these monstrous colliders for a variety of experiments ranging from probing into the structure of atoms to study fundamental forces to creating rare, quickly decaying particles to reveal exotic physics. Nevertheless, whatever particle physicists may be studying, they all covet an accelerator with a high luminosity which is measured in number of collisions per cross-sectional area. The equation for luminosity is given by

$$L = \frac{f N_1 N_2}{\sigma_x \sigma_y} \qquad [1]$$

where f corresponds to the frequency of collisions between colliding beams one and two, the terms N_1 and N_2 each being the number of particles in each respective bunch, while the terms σ_x and σ_y denote the cross-sectional area at the point of collision. The ultimate goal for particle physicists is to increase the frequency and number of particles per bunch while limiting the cross sectional area at the point of collision. These higher luminosities equate to higher rates of collisions, which could mean more data of rare collision events.

The build up of electron clouds can adversely affect the operation of accelerators by impacting beam dynamics that have decreasing effects on the luminosity [3]. The electron cloud is created when synchrotron radiation that is emitted from beam. strikes the inside of the inside of the vacuum chamber of the storage ring. This radiation creates photoelectrons from electrons on the inside of the beam pipe. These photoelectrons then continue to liberate higher-order photoelectrons and eventually an electron cloud forms. When using multiple tightly spaced bunches inside a long train, the electron cloud created by the first bunch will be felt by the following bunch, which then adds its own contribution to the electron cloud. The electron cloud alters the beam dynamics of bunches, effectively displacing bunches away from the ideal operating point, which has adverse effects on luminosity.

CesrTA

CesrTA is a circular particle accelerator buried 40 feet beneath Alumni Field on the Cornell University campus in Ithaca, New York. To create an ultra-relativistic beam of particles, the machine first employs the use of an electron gun to produce a stream of particles which is then subsequently packaged into a tight bunch of particles. These bunches of particles are then accelerated down a 30 meter Linac where they are given energy boosts from correctly timed RF waves generated by Klystrons. About half way down the LINAC rests a Tungsten target, and if desired, can be lowered into the electron's path to yield a bunch of positrons. The resultant bunch of particles then enters the synchrotron where a series of accelerating stations increases its energy between 2.1 and 5 GeV. The bunches resemble long charged "ribbons" of particles with a height and width of 20μm and 200μm respectively and about 1 cm in length and are spaced 4 ns apart to create a bunch train. Once the bunches reach their desired energy, they are injected into the 768 meter storage ring where the energy remains constant.

Inside the storage ring is where measurements are performed, specifically measuring the dimensions of each bunch as well as their position within the beam pipe. For measuring the height and width of a bunch, the synchrotron radiation emitted from the front of a bunch is reflected from a mirror to a CCD camera. This effectively gives the front profile of bunch since the spot size of the synchrotron radiation is the same size as the bunch itself. As for the length of the bunch, the synchrotron radiation spanning the length of the bunch is incident upon a streak camera which uses a photocathode to turn the input of photons into a same-size stream of electrons. These electrons then go through a ramped voltage and are rotated 90 degrees and finally strike a phosphorous screen. A camera captures the image of the screen, and the length of the bunch is finally measured.

Beam Position Monitors (BPMs) are used to calculate the location of the bunch using image charges. Each BPM contains four buttons inside the vacuum chamber that detect the image charge corresponding to the horizontal and vertical displacement in the beam pipe. Figure 1 below shows a cross section of the beam pipe with the orientation of the four buttons.

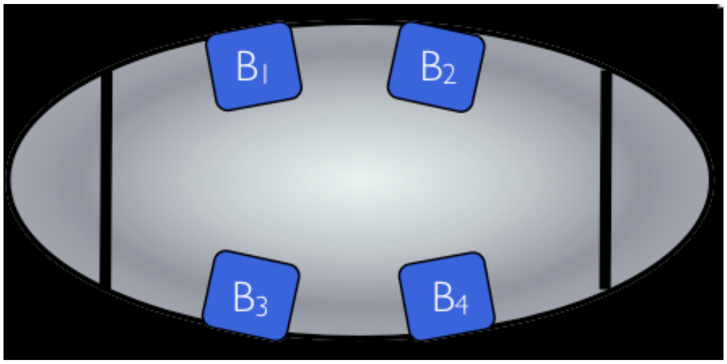

Figure 1 - Cross Sectional View of a single BPM with the four button layout

Using the image charges from the four buttons, the following equations are used to calculate the horizontal and vertical displacement.

$$x = \frac{(B_1 + B_3) - (B_2 + B_4)}{B_1 + B_2 + B_3 + B_4} \quad [2]$$

$$y = \frac{(B_1 + B_2) - (B_3 + B_4)}{B_1 + B_2 + B_3 + B_4} \quad [3]$$

The position of each bunch is made on a bunch-by-bunch turn-by-turn basis so the effects of the electron cloud can be seen throughout the bunch train. One Hundred BPMs exist throughout CESR, each located near a quadrupole magnet. Unlike the dipole magnets which are responsible for guiding the beam around in a circle, quadrupole magnets alter beam dimensions. They act very much like focusing/defocusing lenses in optics, but instead of focusing light, they use magnetic fields to focusing a beam of charged particles depending on the orientation of the magnets. Figure 2 below shows a cross section of a quadrupole complete with magnetic field lines and poles.

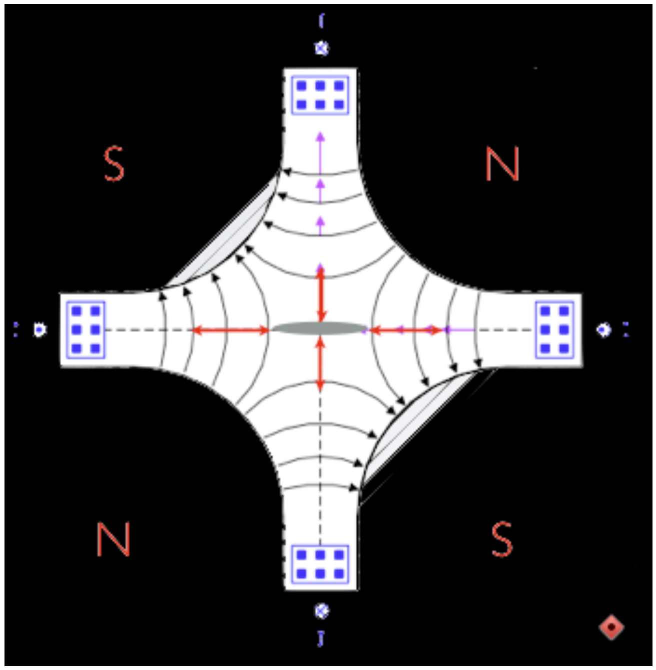

Figure 2 - Quadrupole Magnet Schematic of Horizontal Focusing

With each quadrupole magnet's orientation, in one dimension there will be focusing, while in the other there will be defocusing. Under the orientation in Figure 2 using a bunch of electrons, there would be a focusing effect in the horizontal direction and a defocusing effect in the vertical direction. Each subsequent quadrupole is rotated 90 degrees from its neighboring magnets, so the bunches go through alternating regions of focusing/defocusing effects in each dimension. Much like aligning focusing/defocusing lenses in optics, a series of quadrupoles are placed around the ring to achieve net focusing in each dimension. This focusing/defocusing effect causes the bunches to have trajectories given by the following differential equations:

$$x'' + K(s)x = 0 \qquad [4]$$

$$y'' + K(s)y = 0 \qquad [5]$$

These differential equations are that of possibly the most elegant of simple physics models: the simple harmonic oscillator (SHO). Instead of the *K* being a constant of a spring, the constant depends upon the properties of the strength of the quadrupoles and their lattice orientation around the ring. These oscillations about the horizontal and vertical dimensions are known as Betatron Oscillations where the number of oscillations per turn is known as the tune, which is denoted as ν_x and ν_y for the horizontal and vertical tune respectively. These equations are rather ideal, and only represent equations for single bunch trains. When many bunches are incorporated into a train, these equations become coupled.

These tune values are of special importance because very much like a SHO, resonant frequencies exist. When bunches operate at these resonant tunes, the beam begins to oscillate and the beam oscillation amplitude increases. The oscillation could be driven so much so that the beam could hit the inside of the beam pipe, causing the beam to be lost. Selecting an operating point between points of resonance is ideal, but electron cloud effects could cause tune shifts down the bunch train resulting in later bunches to operate at a resonance point.

Single Bunch Tune Measurement and Analysis

To study how the electron cloud alters beam dynamics in CesrTA, the BPM system was upgraded for data collection on a bunch by bunch turn by turn measurement. the tune is calculated on a bunch-by-bunch turn-by-turn basis. This data was input into a program known as the FFT GUI which contains a variety of different tools to analyze position data that analyzes this bunch by bunch turn by turn data. A screenshot of the program is shown below in Figure 3.

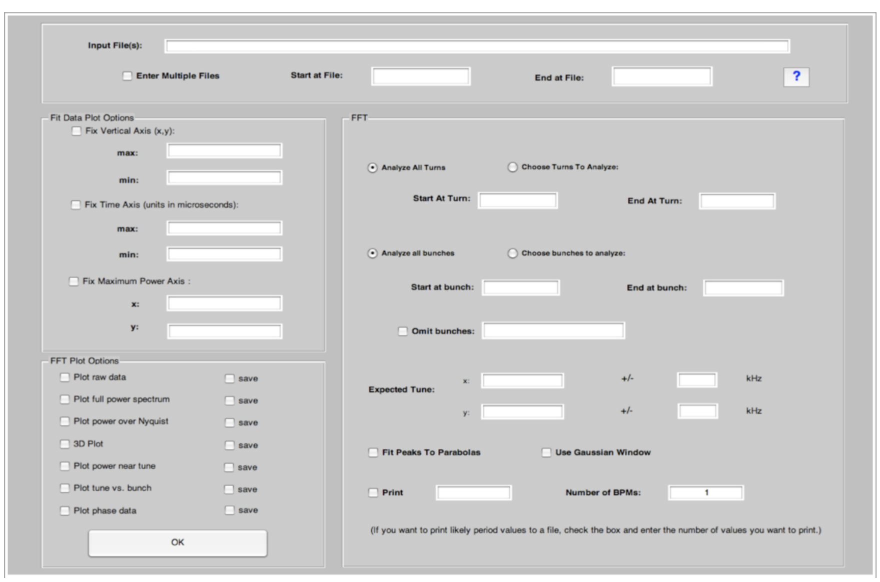

Figure 3 - FFT GUI Screenshot

Under normal circumstances, the tune must be induced. To calculate the tune, position data output by the BPMs in CESR is put through a Fast Fourier Transform (FFT) function that converts the position data which is a function time into a function of frequency. But in order to actually measure this oscillation frequency, each bunch is given a “kick” using a short magnetic pulse to induce an oscillation in either the horizontal or vertical direction. An example of a vertical kick is shown below in Figure 4.

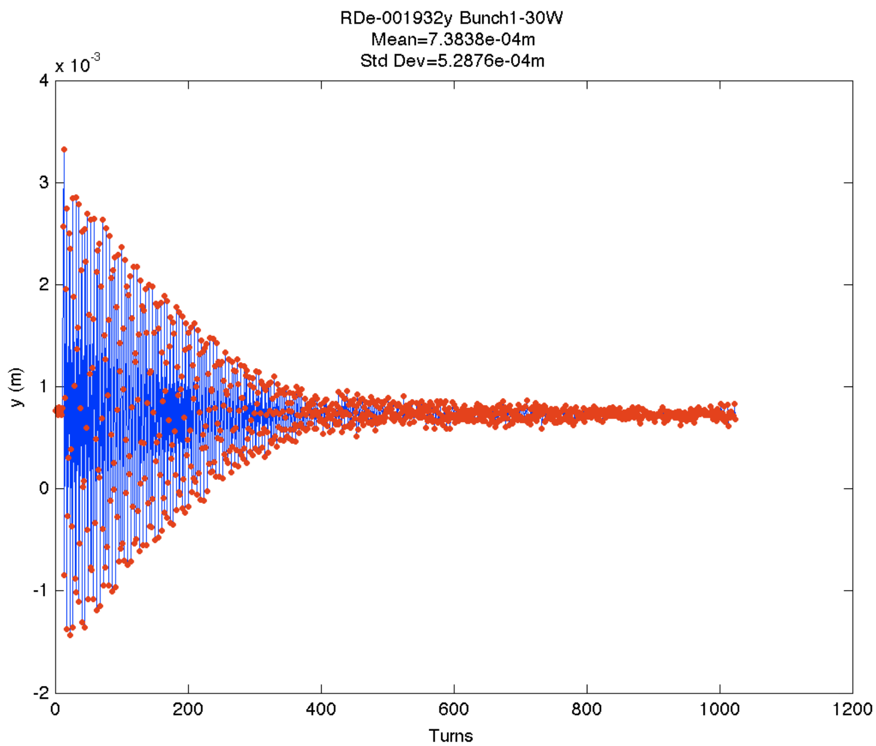

Figure 4 - Induced vertical oscillation of Bunch 1

This plot shows the raw position data output from BPM 30W of Bunch 1 for 1024 turns. Near the beginning of the data collection, a vertical kick causes the beam to oscillate at an amplitude of around 4 mm and this amplitude eventually decreases through time due to radiation damping (energy loss due to synchrotron radiation). Viewing the raw data from multiple bunches along a train, and compiling them into a movie reveals the electron cloud buildup and how this causes the beam to oscillate. Figure 4 shows the first bunch of a ten bunch train, while Figure 5 below shows Bunch 9 for this same train.

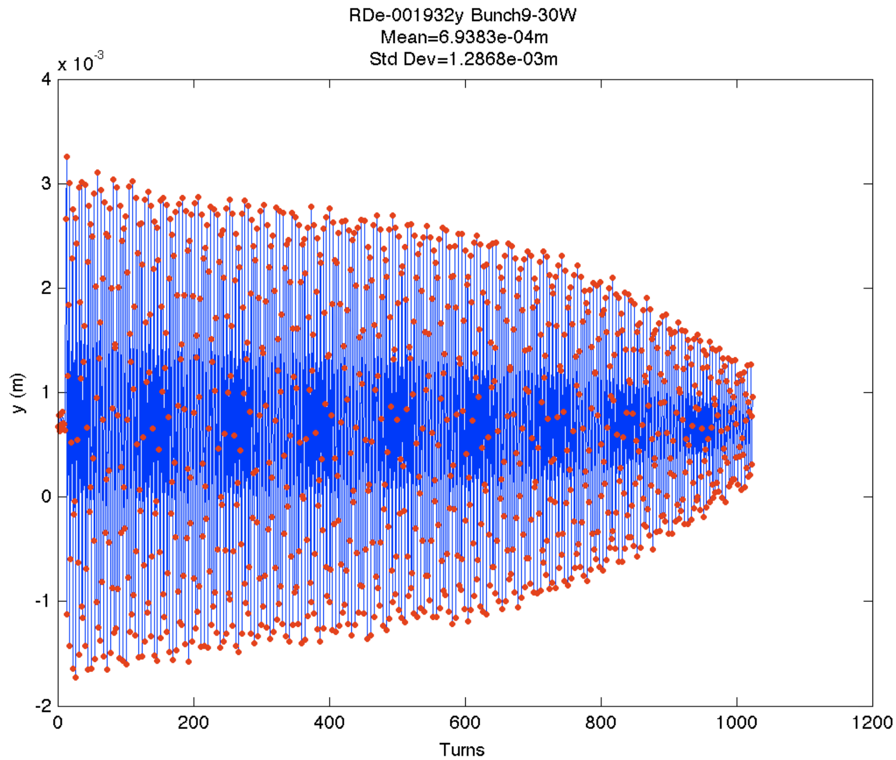

Figure 5 - Induced vertical oscillation of Bunch 9

When comparing Figures 4 and 5, the decay rates of the two oscillation amplitude differs dramatically. 1024 turns after the initial vertical kick, Bunch 1 returns to its normal oscillation in amplitude, while Bunch 9's amplitude barely seems to change. This loss of radiation damping is entirely due to the electron cloud build up from the previous eight bunches in the train which causes the Bunch 9 to continue to oscillate. As the bunches travel turn-by-turn, Bunch 9 continuously experiences the electron cloud produced by the previous bunches because each bunch spacing consists of only 14 ns. These small spacings do not allow the electron cloud to dissipate, resulting in a continuously growing electron cloud. Only when there exists a large space between bunches (~ 100 ns), like that between the last bunch in the train and Bunch 1, does the electron cloud die out and it no longer alters beam dynamics.

To calculate the tunes from the raw position data, the turn-by-turn data is put through the FFT to create a function of frequency. These values are plotted against a power spectrum, and the most prevalent tunes for a particular bunch appear as peaks in the power spectrum. These peaks and their neighboring values are then fit to a parabola to interpolate the correct oscillation frequency.

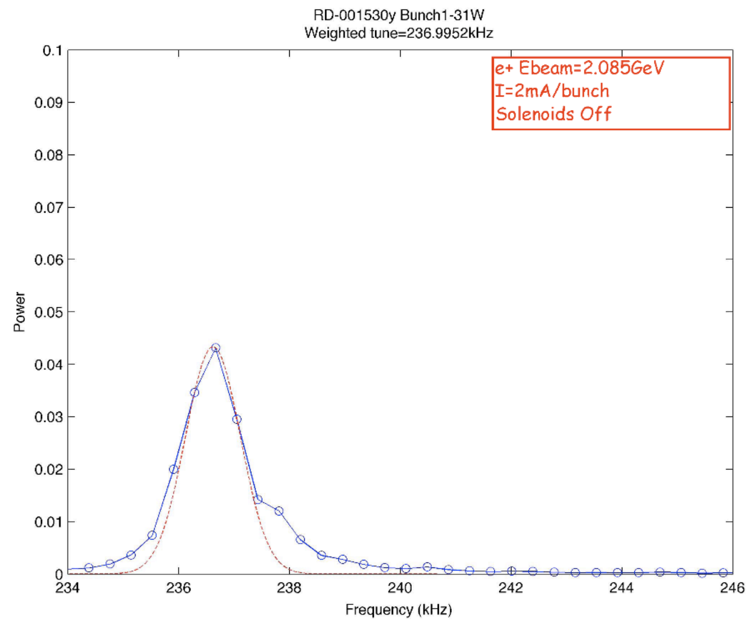

Figure 6 - Tune Calculation of Bunch 1 in a ten bunch train

Figure 6 above shows a sample of plotting the power near the tune of Bunch 1 of a fifteen bunch train. The maximum in power corresponds to the most prevalent tune for this particular bunch at this BPM. Just like with the raw position data, viewing multiple bunches along a train and compiling these images into a movie reviews the electron cloud buildup along the bunch train. Figure 7 below shows how the tune changes down a bunch train with the frequency increasing with each successive bunch in the train.

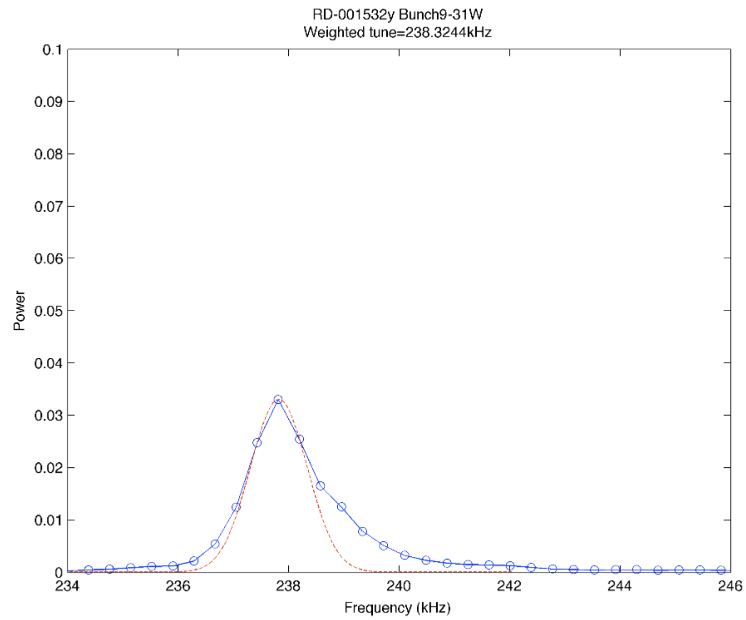

Figure 7 - Tune Calculation of Bunch 9 in a ten bunch train

This figure shows Bunch 9 with a weighted tune of 238.3 kHz which is about 1.3 kHz greater than the initial tune of Bunch 1 at 237 kHz. This increase in tune is known as a tune shift, and is the result of the electron cloud building up the bunch train. These tune shifts need to be monitored closely because they may fall on resonant frequencies that can cause beam instabilities. One way to study the electron cloud density along a bunch trains is through witness bunch studies. These studies involve using a long bunch train to build an electron cloud then injecting bunches at positions following the train to sample the electron cloud. For this experiment, a 10 bunch electron cloud generating train is produced and followed by a single bunch that probes the electron cloud at various postitions. Figure 8 below shows two sets of ten bunch trains followed by witness bunches.

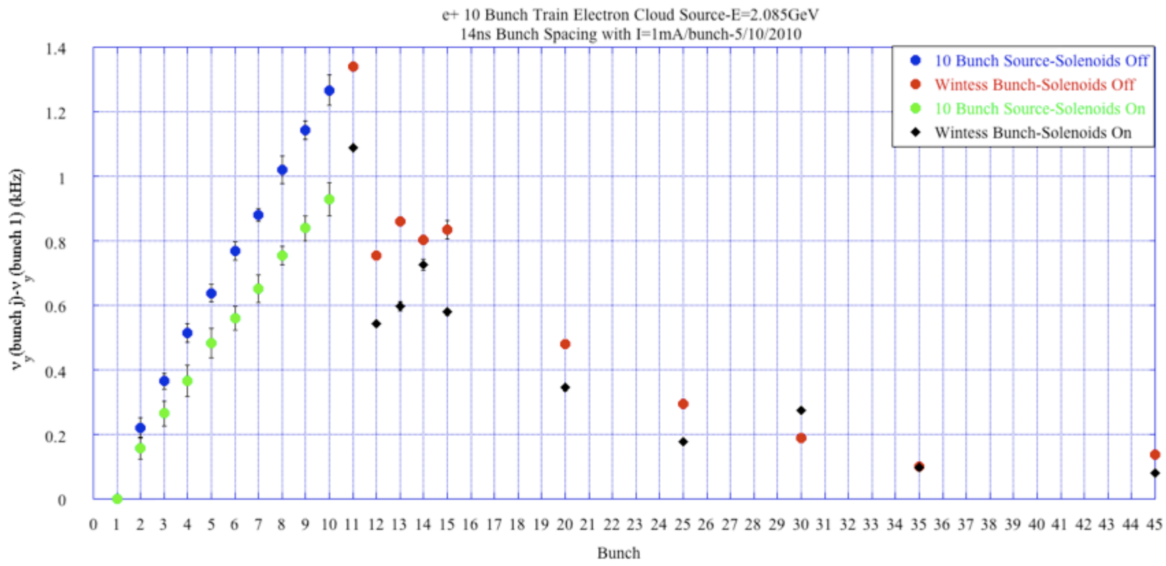

Figure 8 - Witness bunch measurements for ten bunch trains, both solenoids on and off, as well as witness bunch measurements

The green and blue data points represent the ten bunch trains. Moving down each train, the positive vertical tune shifts can be seen increasing as the electron cloud grows. The red and black data points represent the witness bunches that experience the electron cloud at different densities. As the witness bunches are placed further away, the tune shift decreases, indicating that the electron cloud has begun to dissipate. In fact, by measuring these 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:

$$\langle \rho_c \rangle = \gamma \frac{\Delta Q_x + \Delta Q_y}{r_e \langle \beta \rangle C} \qquad [6]$$

where ΔQ_x and ΔQ_y are the horizontal and vertical tunes respectively, <β> is the average beta function, *C* is the ring circumference, *g* is the beam Lorentz factor, and r_e is the classical electron radius [2]. Figure 8 below shows this measured tune shifts (red) compared with simulation (black) using the software *POSINST*. The two calculations correlate very well with each other having similar values for bunches 1-30 [2].

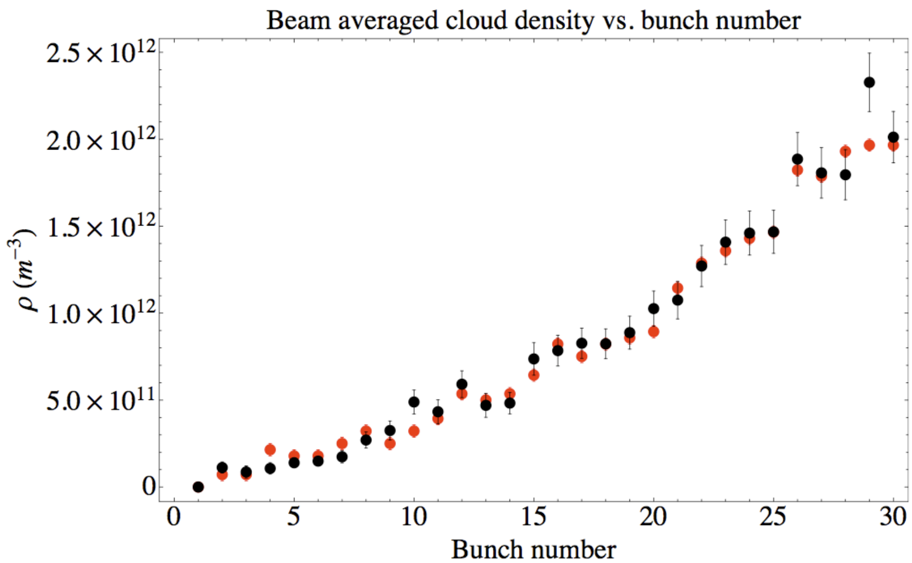

Figure 9 - Electron cloud density studies with measured density compared with simulation

Connection to ILC

CesrTA acts as a testing ground to perform crucial R&D for ILC damping rings. The ILC is a proposed new electron-positron collider that would allow for the exploration of energy regions beyond the reach of today's accelerators. The linear design allows an electron-positron collider to be built to produce collisions > 1 TeV without the production of intense synchrotron radiation. But in order to achieve an adequate collision rate of the electron and positron beams at the collision point, the cross sectional area must be reduced using circular damping rings. These proposed damping rings are similar in size to CESR making it a perfect experiment for studying the electron cloud effects that adversely affect radiation damping. The current density of the very low emittance damped bunches will be greater than has every been achieved in a storage ring, and will be limited by electron cloud effects. For this reason, future research into electron cloud density and betatron tune shifts at CesrTA will greatly influence future ILC damping ring design.

References

[1] D.L Kreinick, et. al., “Using Coherent Tune Shifts to Evaluate Electron Cloud Effects on Beam Dynamics at CesrTA”, IPAC ’11, New York, NY

[2] G.Dugan, et. al., “Studies at Cesr TA of Electron-Cloud-Induced Beam Dynamics for Future Damping Rings”, ECLOUD’ 10, Ithaca, NY, DYN03

[3] G. Dugan, et. al., “Studies of Electron-Cloud-Induced Beam Dynamics at CesrTA”, ECLOUD’10, Ithaca, NY, DYN03.