ELECTRON CLOUD STUDIES AT CESR-C AND CESR-TA*

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Abstract

Over the past year dedicated experiments have been made to characterize the generation of the electron cloud in the Cornell Electron Storage Ring (CESR). In these experiments recently implemented multi-bunch turn-by-turn instrumentation has been employed to characterize vertical beam size blow-up and tune shift for individual bunches along a bunch train. The turn-by-turn instrumentation and electron cloud experiments will be described in this paper. In addition, this paper provides a brief overview of the work that has been done to date and describes future plans to use CESR as a test accelerator (CESR-TA) for International Linear Collider (ILC) Damping Rings research and development. As part of this program we plan to study the impact of the electron cloud on ultra low emittance beams and will undertake measurements of electron cloud growth and suppression in the CESR-c wigglers which were selected for the baseline ILC design.

INTRODUCTION

The International Linear Collider (ILC) Reference Design Report (RDR) specifies single electron and positron damping rings (DR), each with a circumference of 6.7 km [1]. A significant concern for the positron ring is the build-up of the electron cloud (EC) and the potential for electron cloud induced instabilities which can limit the performance of the ring and ultimately the luminosity performance of the collider. Studies carried out for the RDR indicate that the positron DR is likely to operate above the electron cloud instability threshold unless satisfactory mitigation techniques can be demonstrated in the wiggler and dipole chambers. Thus one of the highest research and development priorities for the ILC DR group over the next few years is demonstrating technical solutions in these chambers. In addition, the large extrapolation from conditions in any currently operating positron ring to those of the ILC damping rings requires that we carefully benchmark simulations of the electron cloud growth and its impact on the beam. Therefore experimental studies with parameters more closely approximating the DR parameters are highly desirable. One option for obtaining additional data in a regime that closely approaches the ILC DR parameters is to carry out an experimental program at CESR at the conclusion of the CLEO-c/CESR-c colliding beam physics program in early 2008.

PRESENT INSTRUMENTATION FOR ELECTRON CLOUD MEASURMENTS

A key performance issue for colliding beam or synchrotron radiation production accelerators like CESR is the ability to differentiate between single bunches in a bunch train. To achieve this goal, beam position monitors (BPM) and vertical beam size monitors (BSM) that can measure the tune and vertical beam size for individual bunches on a turn-by-turn basis, have been installed and used for electron cloud studies in CESR.

The vertical beam size monitor consists of a Hamamatsu H7260K 32-channel linear photomultiplier tube (PMT) array (31.8x7mm) [2]. The sub-nanosecond rise time of the PMT allows for digitization of the signal on a bunch-by-bunch basis. In CESR, the PMT array is used to

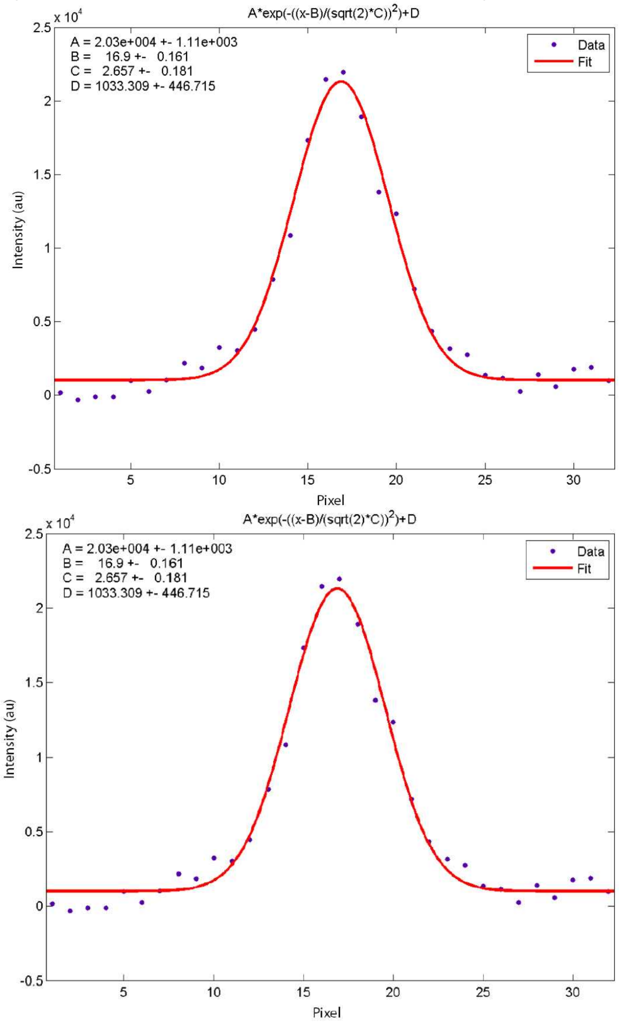

Figure 1. Vertical distributions from the PMT arrays of a single electron (top) and positron (bottom) bunch in CESR.

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measure the vertical profile of individual e+/e- bunches on a turn-by-turn basis. Figure 1 shows the vertical profile of a single electron and positron bunch in CESR where the profile is fit to a Gaussian distribution with a flat background to determine the mean vertical position and width of a single bunch.

Recent upgrades to the CESR beam position monitors have provided the capability for multi-bunch turn-by-turn readout [3, 4]. As a result, single bunch tunes can be determined by: i) exciting the bunches with a pulsed magnet, ii) measuring the position of the excited bunches on a turn-by-turn basis and iii) performing a fast Fourier transform of each bunch's position to determine the oscillation frequency (tune) of the individual bunches. Figure 2 shows the vertical tune for a 10 bunch electron train followed by a 5 bunch witness train that is separated by 56 ns.

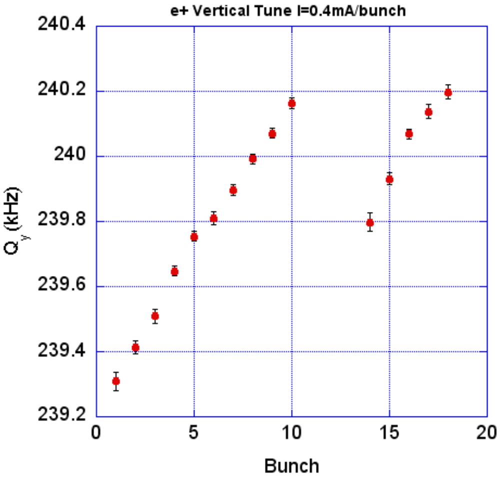

Figure 2. The vertical tune for a 10 bunch train followed by a 5 bunch witness train of positrons with a gap of 3 bunches (56 ns) between the two trains. Note the positive tune shift for the first train of bunches and the tune recoil due to the gap between the main and witness train.

RECENT ELECTRON CLOUD MEASUREMENTS IN CESR

During the past year a series of experiments have been made using the turn-by-turn BSM and BPM systems to quantify the generation of the electron cloud in CESR. The operating parameters of CESR during these experiments are shown in Table 1.

Table 1: Some CESR Parameters

Parameter	Value
Circumference	768.44 m
Revolution Frequency	390.13 kHz
RF Frequency	499.76 MHz
Harmonic Number	1281
Total possible bunches	183 (=1281/7)
Bunch Spacing	14 ns

Figure 3 shows the results from a series of bunch-by-bunch tune measurements where a 10-bunch train of positrons was used to generate the electron cloud and then witness bunches were placed at various distances behind the train. The data was taken during 1.9 GeV operations in a lattice with 12 active wigglers. In this case, all bunches were filled to the same bunch current of 0.75 mA corresponding to approximately 1.2x10^{10} particles/bunch. The tunes of all bunches are plotted relative to the tune of the leading bunch in the train. In a simple model of the interaction between the EC and the beam, the cloud density required to produce the vertical tune shift along the train is ρ_e~10^{11}/m^3/kHz [5]. We note that the vertical tune data is consistent with the witness bunches seeing a cloud density that decays with a nominal time constant of roughly 170 ns. In contrast with the vertical tune shift, the horizontal tune shift shows very little variation down the length of the train. This observation can be explained by the horizontal distribution of the EC in the vacuum chamber [6].

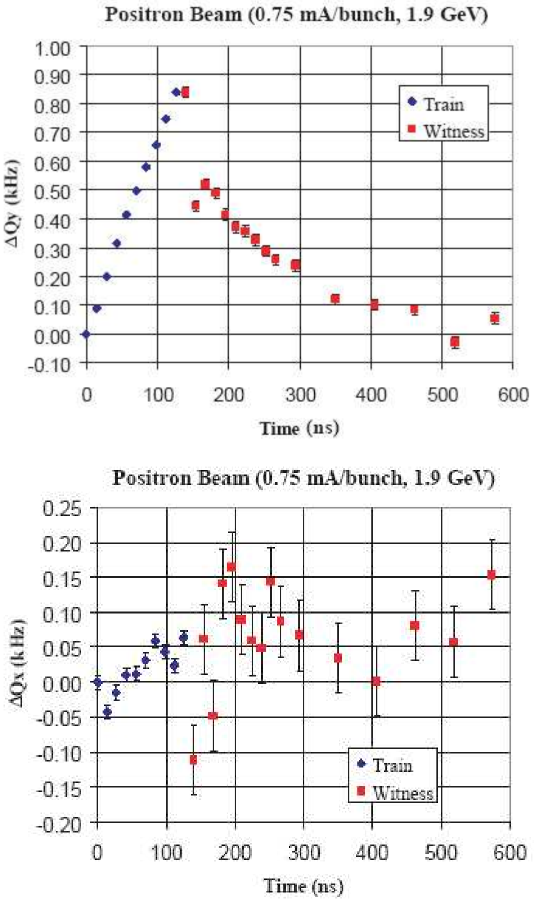

Figure 3. Results of a sequence of witness bunch measurements with a positron beam. Each witness bunch point corresponds to an individual measurement with that bunch trailing the initial 10 bunch train. The initial train acted as a generator of the electron cloud. The tunes were measured for bunches in the leading train and the witness bunch in each case. The top plot shows the shift in vertical tune of each bunch relative to the leading bunch.

The bottom plot shows the same information for the horizontal tune. The nominal first bunch tunes were Q_x=202.7 kHz and Q_y=239.3 kHz.

For comparison with the positron data, the same series of measurements was carried out for an electron beam. Figure 4 shows the observed tune shifts for electrons. Note that the sign of the vertical tune shift is consistent with the electron cloud acting on an electron beam. For the later witness bunches, the vertical tune shift decays with a time constant in excess of 100 ns in a similar fashion as observed for the positron beam. Also note that the tune shift of the first few witness bunches after the leading train continues to grow. We hypothesize that this may be due to the electron cloud equilibrating to higher densities near the beam axis after the end of the train has passed. We are starting to investigate this behavior in simulation to help understand this observation in detail.

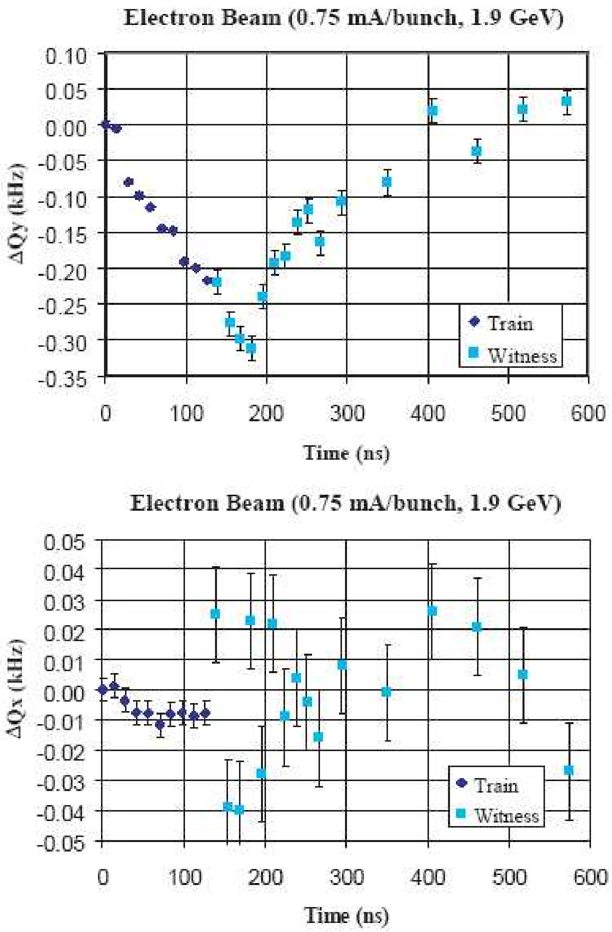

Figure 4. Results of a sequence of witness bunch measurements with an electron beam. Each witness bunch point corresponds to an individual measurement with that bunch trailing the initial 10 bunch train. The initial train acted as a generator of the electron cloud. The tunes were measured for bunches in the leading train and the witness bunch in each case. The top plot shows the shift in vertical tune of each bunch relative to the leading bunch. The bottom plot shows the same information for the horizontal tune. The nominal first bunch tunes were Q_x=203.7 kHz and Q_y=241.4 kHz.

Figure 5 provides an overlay of the positron and electron vertical tune data. The magnitude of the observed tune shift along the leading train for electron beam is approximately 1/4th that observed for the positron beam.

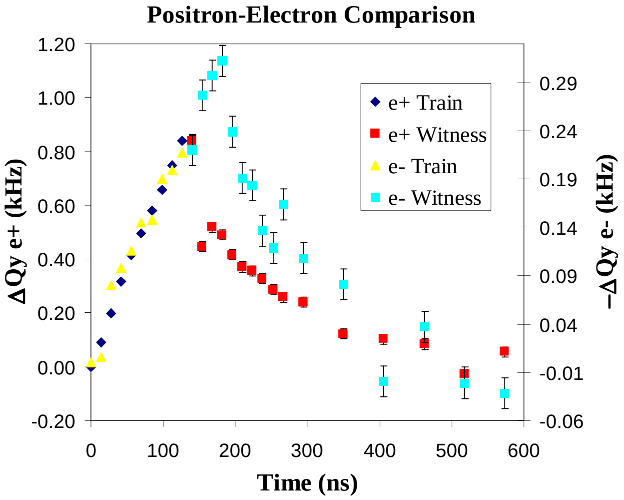

Figure 5. The graph shows an overlay of the electron and positron vertical tune data from Figures 3 and 4. Note that the electron vertical tune shift is negative.

In addition to quantifying the tune shift in the presence of the electron cloud, the bunches' vertical beam sizes were studied. Figure 6 shows plots of a series of vertical beam size measurements along 45 bunch trains of positrons for a range of bunch currents. Each point consists of the average of 200 50-turn samples. A Gaussian fit to each 50-turn sample provides profile information. The 50-turn averaging of the PMT signals mixes the effects of centroid motion and incoherent beam blowup. Subsequent measurements have demonstrated that both effects are present after the onset of the instability. The onset of the instability in each case occurs when approximately 1.5×10^{11} beam particles have preceded the first bunch exhibiting the instability.

In summary, beam measurements at CESR show evidence for generation of an EC along a train of positron bunches and the development of an EC-induced instability for bunches at the end of sufficiently intense trains. Similar measurements with trains of electron bunches show tune shifts along the trains which are also consistent with the presence of the EC, but with smaller magnitude than seen for positron beams. Work is underway to understand these observations in greater detail through simulations.

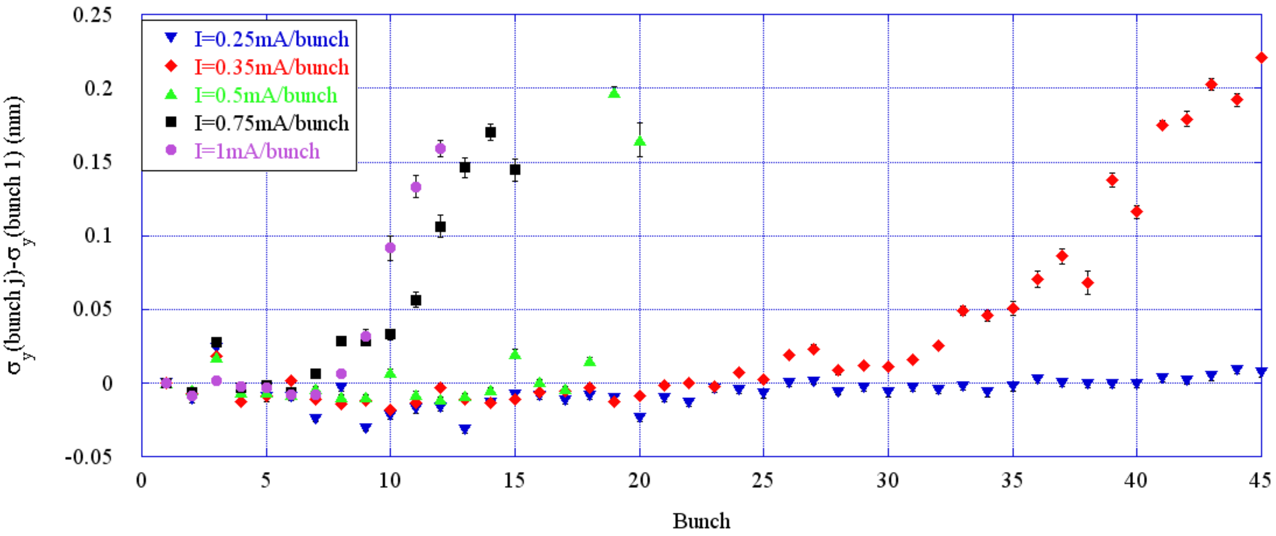

Figure 6: Onset of a vertical beam size instability for trains of 45 positron bunches as a function of bunch current. For the measurements shown, each point corresponds to the average of 200 single bunch beam size fits where each fit was carried out on a 50-turn average of the PMT array signals.

THE CESR-TA PROGRAM

General Description of CESR-TA

With minimal modifications to CESR, the CESR-TA program offers several unique opportunities for carrying out ILC DR research and development. The goal of the CESR-TA program will be to support key research and development on the timescale of the ILC Engineering Design Report (EDR) which is targeted for publication in 2010. We intend to offer a program complementary to the ongoing research program at the KEK-ATF. Such a program will help satisfy the needs for ILC DR experimental studies as research at ATF begins to focus more heavily on beam delivery system studies as part of ATF-II [7].

Since CESR is the only operating wiggler dominated storage ring in the world it provides a benchmark for producing ILC damping ring beams. By configuring CESR for ultra low emittance operation, we will be able to explore the onset of EC induced instabilities and the sources of emittance growth for beams with parameters in the same regime as those in an ILC DR. Design studies have been carried out to characterize our ability to utilize CESR as a test bed for key ILC damping rings R&D [8].

Producing ILC-like Test Beams at CESR-TA

The CESR-c damping wigglers are the baseline technology choice for the ILC damping rings due to their large physical aperture, which is critical for the acceptance of the positron DR, and their excellent field quality, which ensures that the dynamic aperture of both rings is acceptable [9, 10]. In its low energy configuration (beam energies between 1.5 and 2.5 GeV) with 12 damping wigglers, CESR operates as a wiggler-dominated storage ring. By placing the 12 wigglers in zero dispersion regions, CESR will be capable of reaching ultra low emittances in this mode. In addition, the CESR energy range is 1.5 – 5.5 GeV, allowing key system tests at the ILC DR operating energy as well the ability to characterize and differentiate beam dynamics issues through their energy dependence. Finally, the ability to store both positrons and electrons in the same ring will allow species-dependent effects to be clearly distinguished.

A baseline ultra low emittance lattice has been designed where the CESR-c wiggler magnets have been moved to zero dispersion regions. A summary of the design parameters and twiss parameters for the ultra low emittance lattice are located in table 2 and figure 7 respectively. Correction algorithms to achieve ultra low emittance and tuning methods to maintain these conditions will be studied along with developing instrumentation to characterize these extreme conditions.

Studies of the alignment sensitivities for the CESR-TA lattice indicate that, with a careful program of magnet alignment, it should be possible to correct the ring to operate with a vertical emittance of a few to several picometers (< 8 pm at 95% confidence level) [8].

Beam diagnostics and feedback upgrade for CESR-TA

In order to characterize ultra low emittance beams, we are developing a fast x-ray camera based on Gallium Arsenide (GaAs) diode technology. The fast response times of GaAs photodiodes (30-50 ps) allows for the possibility of true turn-by-turn multi-bunch measurements. An x-ray camera offers the possibility of measuring beam sizes of individual bunches with micron resolution not achievable with visible light cameras. With a suitable x-ray optics system, this type of device has the potential to make turn-by-turn profile measurements of all bunches in a train. Basic components are presently being tested with the help of colleagues at the Cornell High Energy Synchrotron Source (CHESS).

Table 2: CESR-TA ultra low emittance baseline lattice parameters

Parameter	**Value**
No. of Wigglers	12
Wiggler Field	2.1 T
Beam Energy	2.0 GeV
Energy Spread ($\Delta E/E$)	8.6×10^{-4}
Vertical Emittance	5 – 10 pm
Horizontal Emittance	2.25 nm
Transverse Damping Time	47 ms
Q_x	14.57
Q_y	9.62
Q_z	0.075
Total RF Voltage	8.5 MV
Bunch Length	9 mm
Momentum Compaction	6.4×10^{-3}
τ_{Touschek} ($N_b=2\times10^{10}$ & zero current ε_y=5pm)	>10 minutes
Bunch Spacing	4 ns

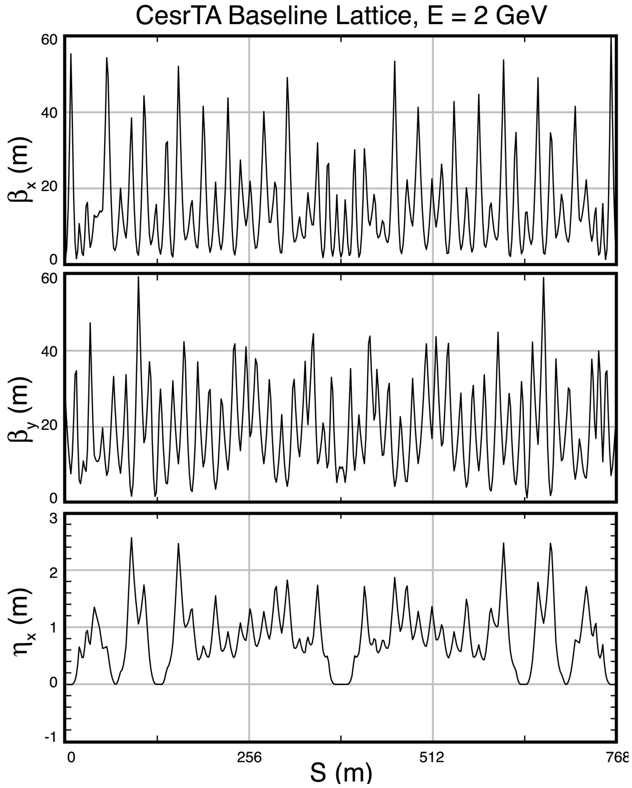

Figure 7. Betatron function and dispersion for the ultra low emittance lattice. CESR-c wiggler magnets will be located in the CESR-c interaction region to take advantage of zero dispersion.

The bunch spacing specified for the ILC damping rings is 3.08 ns. CESR-TA will operate with 4 ns bunch spacings in order to closely approximate the ILC DR specifications. Upgrades to the CESR transverse feedback for 4 ns operation have been made and successfully tested. A longitudinal feedback system upgrade is currently under development. Longitudinal dynamics will be monitored using a 2 ps resolution streak camera. The x-ray and streak cameras make it possible to quantify transverse and longitudinal dynamics for ultra low emittance beams.

CESR-TA for International Linear Collider Damping Ring R&D

A primary focus of the CESR-TA experimental program will be to implement and test technical solutions for mitigating electron cloud growth. Operations with ultra low emittance beams and the ability to flexibly operate the ring with positron or electron beams will permit detailed studies of electron cloud and ion effects in a regime approaching that of the ILC DR. The development and application of advanced diagnostics and techniques for low emittance tuning and maintenance will be an integral part of the operational program. Also, support will be provided for collaborators who want to test DR prototype hardware in the CESR ring.

Specific experimental plans include: i) the study of electron cloud growth and suppression in wiggler, dipole, and quadrupole vacuum chambers and instrumenting key sections of the ring with electron diagnostics. Recently the first retarding field analyzers to characterize local electron build-up in the CESR ring were installed. ii) Exploring the range of electron cloud mitigation techniques including clearing electrodes, coatings and, possibly, grooved chambers. Development is underway on vacuum chambers with collectors that can be employed to characterize electron cloud growth in the CESR-c wiggler magnets. iii) Study of beam dynamics of emittance diluting effects due to the electron cloud and fast ion instability. By offering dedicated experimental runs along with flexible shutdown periods to install experimental hardware, we hope to provide a flexible venue for research by our ILC DR collaborators.

CONCLUSIONS

Recent instrumentation upgrades to CESR have enabled measurements of bunch-by-bunch tune shifts and beam profiles along bunch trains of positrons and electrons in CESR. Measurements of the vertical tune shift for electron and positron beams are consistent with electron cloud build-up along the trains for both species. In contrast to the observed vertical tune behavior, the horizontal tune shows a much smaller variation down the length of each train which can be explained by the horizontal distribution of the cloud in the vacuum chamber. Witness bunch studies with both beams indicate a long decay of the cloud with time constants in excess of 100 ns.

For positron beams, we also observe the onset of a vertical instability that moves forward in the train as the bunch currents are increased. The bunch at which the onset of the instability occurs correlates closely with the total amount of current preceding that bunch in the train.

Starting in 2008, we hope to begin a dedicated program to study the EC with ultra low emittance beams and to help validate suitable EC mitigation techniques for the ILC damping rings. A proposal to support this effort has recently been submitted jointly to the U.S. NSF and the U.S. DOE.

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